CONFIDENTIAL

IMPROVED SCREEN FOR REAR PROJECTION VIEWERS

Technical Report No. - 4

CONFIDENTIAL

CONFIDENTIAL

CORNING GLASS WORKS

ELECTRO-OPTICS LABORATORY

RALEIGH, NORTH CAROLINA

IMPROVED SCREEN FOR REAR PROJECTION VIEWERS

Technical Report No. - 4
(Final Report of First Program Phase)

Date - November 5, 1965

Period Covered - July 15, 1965
to
November 5, 1965

THIS DOCUMENT CONTAINS INFORMATION AFFECTING THE NATIONAL DEFENSE OF THE UNITED STATES, WITHIN THE MEANING OF THE ESPIONAGE LAWS, TITLE 18, U.S.C., SECTIONS 793 AND 794. THE TRANSMISSION OR REVELATION OF WHICH IN ANY MANNER TO AN UNAUTHORIZED PERSON IS PROHIBITED BY LAW.

EXCLUDED FROM AUTOMATIC REGRADING; DOD DIR 5200.10 DOES NOT APPLY

25X1

CONFIDENTIAL

Table of Contents

I. Introduction	1
II. Literature Search	2
A. Open Literature	2
1. Light Scattering Screens	2
a. Rear Projection Screen Parameters and Their Influence on the Display System	2
b. Sensitivity to Ambient Light	18
c. Resolution	19
d. Performance Ratings for Screens	20
2. Other Approaches	21
a. Fresnel Screens	21
b. Lenticular Screens	23
c. Fiber Optics Screens	25
B. Patent Literature Search on Rear Projection Screens	33
1. Lenticular Screens	33
2. Fresnel Screens	40
3. Dynamic Screens	43
4. Hybrid Screens	44
5. Unrelated Patents	45
III. Preliminary Theoretical Investigation	50
A. Applicability of Modulation Transfer Function Theory to the Assessment of Rear Projection Screen Resolution	50
1. Theoretical Basis of Modulation Transfer Function Theory	53

		2.	Experimental Techniques Based on MTF Theory	57
			a. Direct Measurement of Sinusoidal Objects and Images	58
			b. Spread Function Analyses	61
			c. Interferometric Techniques	68
		3.	Conclusion	68
	B.		Losses in Uncoated Hollow Glass Fibers	76
IV.			Preliminary Investigations of CGW Materials	82
	A.		CGW Materials to be Studied in More Detail	82
		1.	Glass Ceramics	82
		2.	Photosensitive Glasses	83
		3.	Multiform Glasses	84
		4.	Porous Glasses	84
		5.	Fiber Optics Materials	85
	B.		Laboratory Investigations	86
		1.	Spectrophotometer Measurements	86
		2.	Samples of Optical Fibers	88
		3.	Metallizing of Hollow Fibers	88
V.			Conclusion	90
VI.			Proposed Program for Phase II (Theoretical Investigations)	91
	A.		Introduction	91
	B.		Theoretical	91
		1.	Scattering	91
		2.	Resolution	91
		3.	Analysis of Projection Systems	91
	C.		Instrumentation	92
	D.		Materials Investigations	92

I. Introduction

This constitutes the final report of the first phase of the program, namely the literature search, from the Contract, "Improved Screens for Rear Projection Viewers". The overall objective of this effort is to investigate Corning Glass Works' materials for applications in rear projection screens. It is to cover only materials and processes which are available with at most only minor modifications. Thus whatever success is achieved will be transferable with little delay into practical screens.

The search covered all the world literature and both domestic and foreign patent literature from 1945 to date. It is felt that all pertinent articles on rear projection systems and screens have been obtained. In addition, a wide variety of literature, to be used to support the theoretical and experimental phases of the program, was collected.

Much additional work has been accomplished in addition to the stated objective of the literature search for this phase of the program. The literature has already been used to guide some preliminary theoretical work on screen resolution and its measurement and is reported in Section III.

We have also started preliminary experimental investigations into CGW materials to help guide the theoretical and experimental phases of the program. This effort is expected to direct the theoretical work toward definite investigations which will make it more directly applicable to the material investigations. Already a wide variety of promising materials have been examined. The first results of this appear in Section IV.

II. Literature Search

A search of all available world literature, constituted the first phase of a program to investigate the applications of CGW materials for rear projection screens. This covered all the open literature and both domestic and foreign patent literature from 1945 to date. The open literature search was extended to the Library of Congress in Washington, D. C. by our technical librarian.

Articles relating to many other fields besides rear projection were collected to support our theoretical and experimental investigations of light scattering phenomena. This literature also covers laboratory instrumentation which will be required for the experimental phase of our work. However, because of the large quantities and little immediate direct application of this literature only that directly related to rear projection screens is discussed.

A. Open Literature

1. Light Scattering Screens

a. Rear Projection Screen Parameters and Their Influence on Display Systems

The function of a rear projection screen is to accept an image from a projector on one side and present it to viewers on the other. To do this it must diffuse and reradiate the incident illumination. The type of projectors in use range from television screens[1] to conventional slide projectors. The effectiveness of such a display system is governed by the characteristics of the screen and by the geometries under which it is illuminated and viewed. To illustrate this, the type of screen used with a microscope projector is made to be viewed by only one person positioned directly in front of the screen and makes use of a narrow-angle, high-gain screen. This type of screen gets the maximum use out of a limited amount of light. On the other hand, a compact sales demonstration unit with a short focal length projector and a widely spread audience requires a wide-angle, low-gain screen.

The behavior of a typical rear projection screen is illustrated in Figure 1. This shows a projector, a screen and an observer.

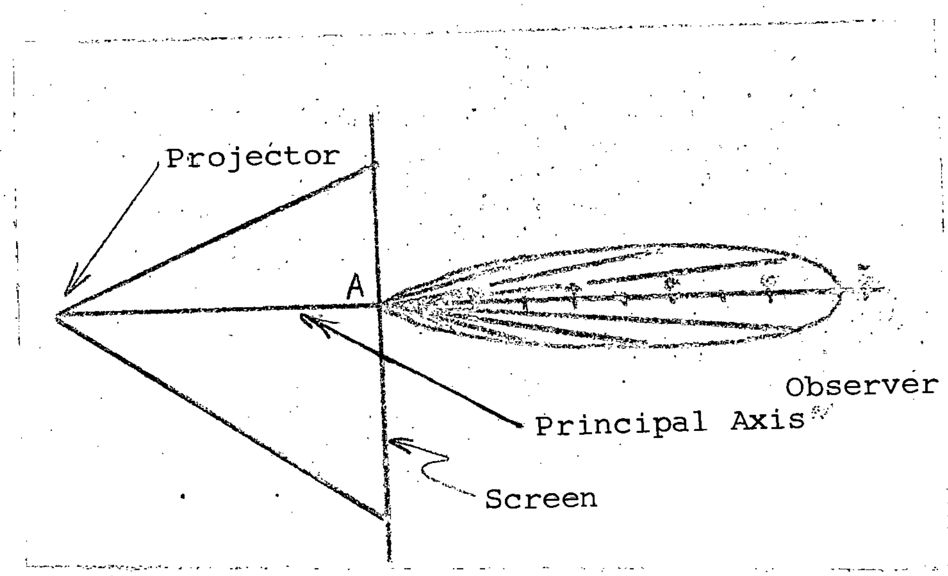


Figure 1. Typical Scattering Pattern from a Rear Projection Screen

A light ray is shown incident upon the screen at point A. Continuation of the line representing an incident ray establishes a "principal axis". The observed brightness of point A from any direction is indicated by the length of the arrows. An observer along the principal axis will observe the screen to be brightest. As he moves around and views the same point on the surface it will become less and less bright the greater the angle. This angle is called the "bend angle".

Transmission, reflection and absorption account for all of the properties of rear projection screens aside from diffusion. The scattering properties of screen materials have been discussed in a number of good articles[2-8]. A plot of the scattering distribution shows the relative intensities, $I(\theta)$, of rays of light which are deviated at different angles by the screen[5,9]. The curve is obtained by measuring, with a goniophotometer or comparable instrument, the brightness of a narrow parallel beam of light as it is spread out by the screen. These intensities are then normalized to a perfect Lambertian diffusing surface where the intensity of the scattered light is proportional to cos θ. This establishes the reference as equivalent to a unity gain diffuser. Lambertian diffusers are approximated by coatings of either Magnesium Oxide (MgO) or Magnesium Carbonate. Screens which do not diffuse as uniformly as the standard reference will appear brighter than the standard over a certain range of viewing angles. The distribution curve will have a value greater than unity in this region. Because a diffusing screen is a passive element which does not add energy to the light passing through it, any increase in gain above unity for one viewing position must necessarily result in a gain less than unity for some other position. Often the singular term "screen gain" is used and is the value of the gain curve at $\theta = 0$. An extensive investigation of commercial screen materials has been reported[10].

It would be more correct to call these curves relative gain curves as they are relative to the standard Lambertian diffuser. Figure 2 shows a typical set of relative screen gain curves. Although this parameter is useful for comparing screen scattering distributions it shows little or nothing about efficiency. The absolute gain curve is a measure of efficiency and is found by multiplying the scale factor of the relative gain curve by the diffuse transmission coefficient of the screen. This is simply the ratio of the intensity through the screen to the incident intensity, regardless of angle. Hence two screens which have identical relative gain may have significantly different absolute gain. It is also important to note that viewing requirements generally call for greater viewing angles in the horizontal plane than in the vertical. This necessitates a screen which is anisotropic, i. e., the gain curve should be broad for the horizontal plane and relatively narrow for the vertical[9].

In general the distribution curves for rear projection screens differ significantly from Lambertian diffusers, though not enough to be treated according to the laws of specular reflection or direct transmission.

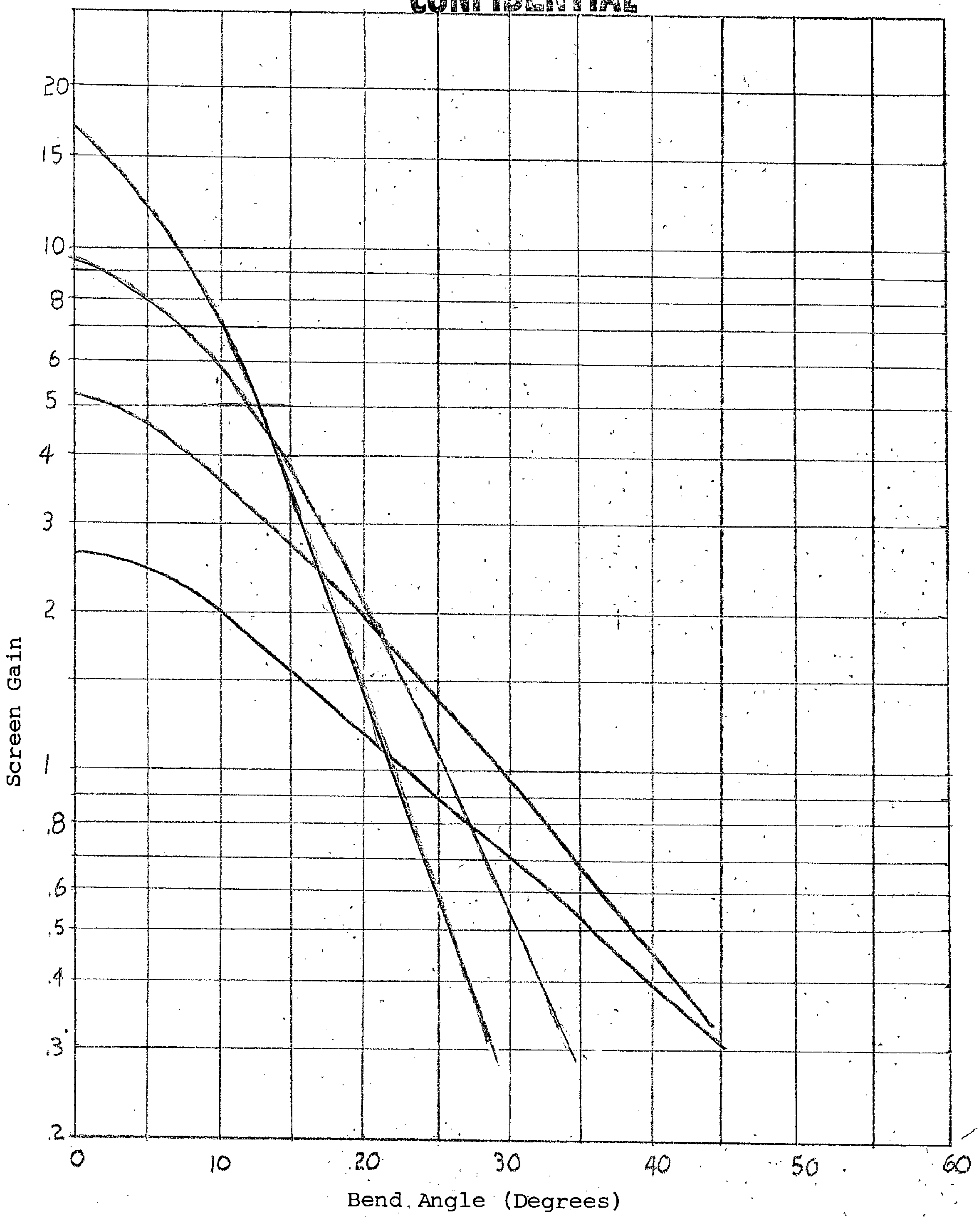


Figure 2. Screen Gain as a Function of Bend Angle for Several Typical Screens

It has been shown these distribution curves can be closely approximated by using some power of the cosine[11], i.e.,

$$I(\theta) = \cos^{s}\theta$$

where the parameter s is termed the "shape factor" and provides a convenient index to the diffusing characteristics of a screen and usually takes on values between 1 and 50. Still a better fit is obtained if a modified cosine distribution is used[3] where s is expressed as a function of the angle θ in the form

$$s(\theta) = s_o \exp -k(s_o - 1)\theta^{m}$$

The parameters s_o, k, and m have been used as figures-of-merit in specifying suitable screen characteristics. Still a third empirical formula to describe the angular distribution of light from screens has been proposed[12]. However it has not produced the good fit obtained using the modified cosine power relation. Figure 3 shows two typical gain curves and the approximations using the three different empirical formulas[3].

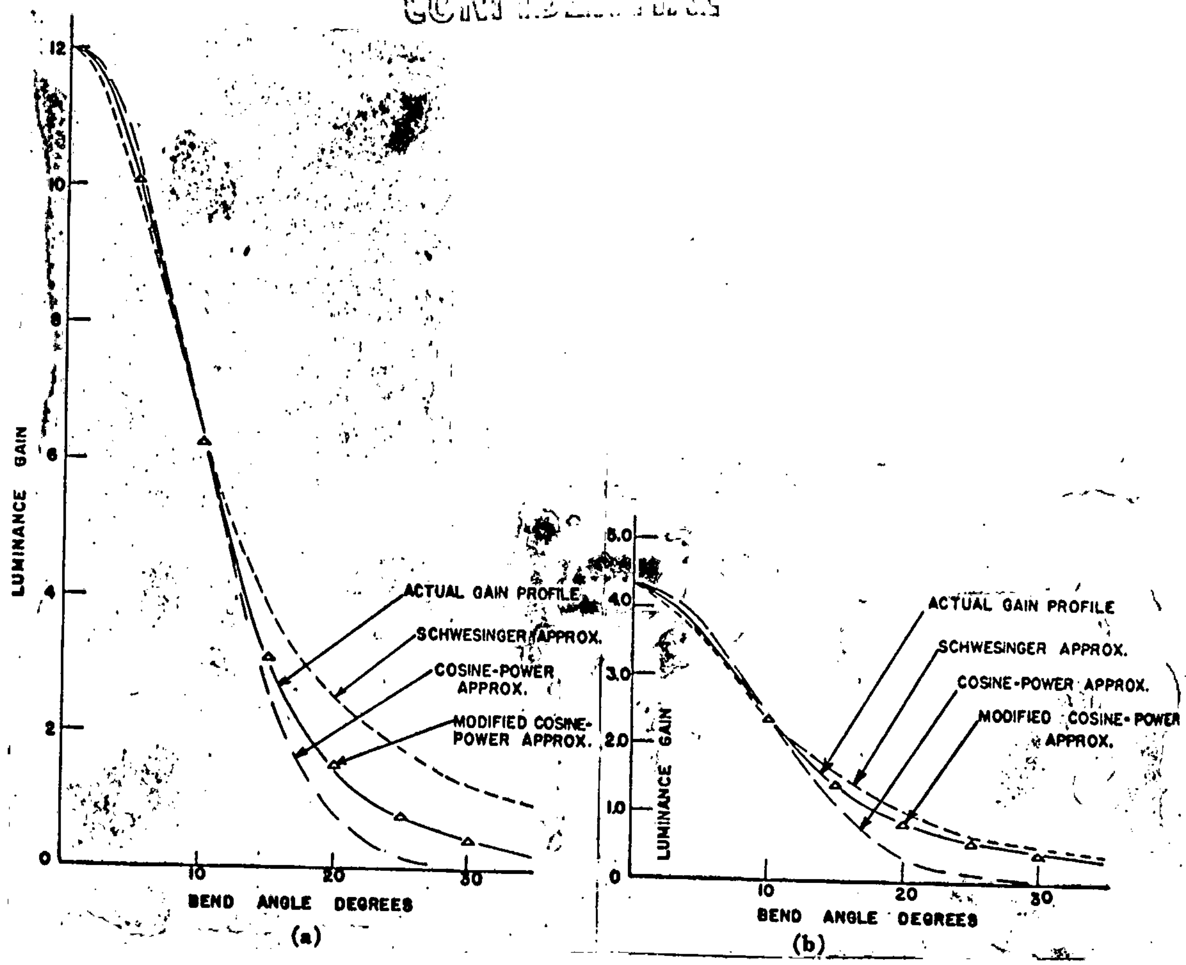


Figure 3. Theoretical Fitting of Actual Gain Profiles: (a) Typical High-Gain Profile; (b) Typical Low-Gain Profile.

It can be seen from Figure 2 that because the screen gain falls off at increasing bend angles and the screen subtends a finite angle at the observer its surface will appear to be nonuniformly illuminated. The degree of nonuniformity will be dependent upon the angular size of the screen and the shape of the distribution curve. The intensity distribution across the screen can be made more uniform if the scattering distribution is broader but this will be accompanied by a decrease in the overall gain of the screen.

The physical incompatability of low back-scatter and uniform screen brightness in rear projection screens with random diffusion is well established by photometric measurements and is also theoretically understood[13]. The two basic processes responsible for the light diffusion in transmitting screens are; scattering by randomly distributed microscopic or submicroscopic particles, and reflection and scattering at boundaries with random surface irregularities. Scattering by sperical particles of a size of the order of the wavelength diffuses the incident light beam in such a manner that the greatest intensity occurs in the forward direction with a sharp decrease to the side and rear. Multiple scattering makes the intensity distribution more and more uniform. While the forward intensity distribution is flattened, the backscattering increases so that there is an inverse relationship between the peak forward brightness and the intensity of the backscattered light[14-17]. This is illustrated in Figure 4.

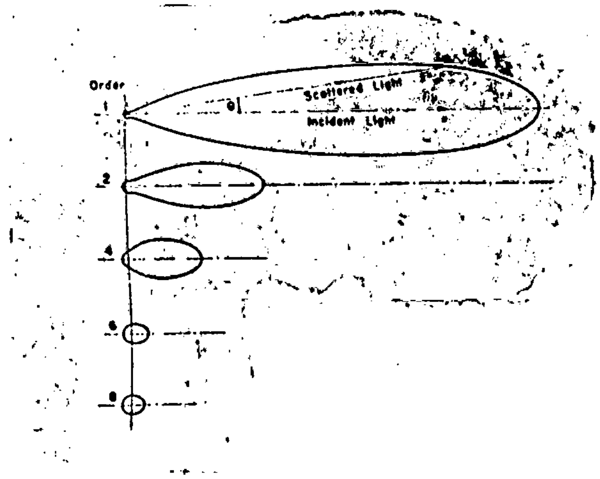


Figure 4. Polar Diagrams for the Distribution of Light Repeatedly Scattered by Particles of Diameter 1.6 μ and Refractive Index 1.25.

Therefore a high diffusion screen, aside from not having as much light scattered in the forward direction, cannot appear as bright as a higher gain screen. The correlation between the forward peak brightness and back-scattered intensity in randomly diffusing screens has been shown[12] and is reproduced in Figure 5.

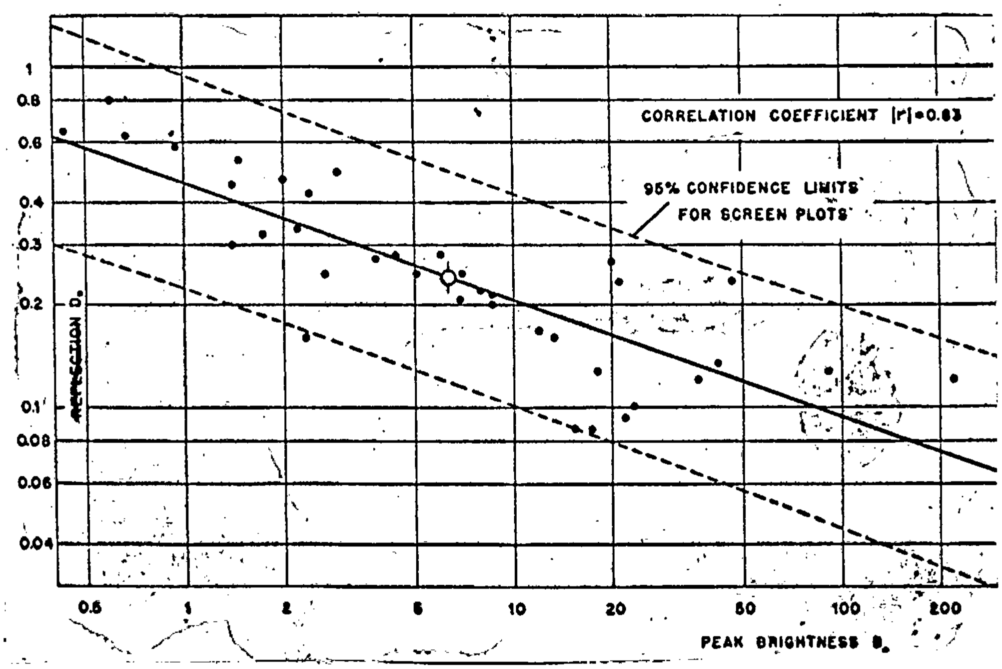


Figure 5. Correlation Between Forward Peak Brightness B and Backscattered Brightness D in Randomly Diffusing Screens

Thus there seems to be some basic limitation as to screen efficiency for a given gain distribution. This limitation may or may not ultimately restrict a given projection-display system depending on the requirements established.

If, rather than using a more diffusing screen, the intensity from the projector is increased, the screen brightness becomes more uniform. An apparent spreading out of the light from the center to the edges will be seen, rather than a simple uniform increase in light intensity. This is because of the logarithmic response of the eye to variations in intensity.

To illustrate this let the intensity at two places on the screen be I_1 and I_2 where $I_1 > I_2$. The perceived intensities B_1 and B_2 will then be

$$B_1 = \log I_1$$

$$B_2 = \log I_2$$

Thus the perceived intensity ratio B_r is

$$B_r = \frac{B_1}{B_2} = \frac{\log I_1}{\log I_2}$$

If now the incident intensity on the screen is increased by a factor α, $\alpha > 1$, the intensities I_1' and I_2' will be

$$I_1' = \alpha I_1$$

$$I_2' = \alpha I_2$$

and the perceived intensity ratio becomes

$$B_r' = \frac{B_1'}{B_2'} = \frac{\log \alpha I_1}{\log \alpha I_2} = \frac{\log \alpha + \log I_1}{\log \alpha + \log I_2}$$

Because $I_2 > I_1$ the addition of $\log \alpha$ to each will proportionally increase the denominator more than the numerator, thus the ratio will become smaller which means by increasing the projector output the screen illumination will tend to become more uniform. Obviously the converse is true if $\alpha < 1$ the denominator will again be more strongly affected and the illumination will become more nonuniform.

Factors such as absolute screen brightness, and the response of the eye are treated extensively in the literature[18-23], as are the closely related areas of color vision, color sensitivity[24-27] and legibility[28]. The fundamental concepts of light and lighting appear in the literature[29] along with discussions and definitions of lighting terms[30].

The closeness of the audience to the screen is also an important factor in determining the desired gain characteristics. The closer the screen is to the audience the larger the bend angles involved, hence the requirements for a uniform picture increase. The width of the screen also has a comparable effect. The wider the screen the greater the range of bend angles hence the problem of projecting an acceptable picture is more difficult. It is important to note that the screen may be brighter overall for an observer at the center of the audience than for one at the edge. However it has been found that it is more important to view a uniformly illuminated image than a brighter nonuniform picture, although in any case, brightness must be sufficient for all viewers to watch with comfort.

Matters are further complicated as light entering the screen is scattered more and more with deeper penetration. Maximum scattering has occurred by the time the light reaches the back surface. Here the scattering distribution will have values for all possible angles. Because the light must now pass from a medium of higher refractive index into a medium of lower index all of the intensity scattered at an angle greater than a critical angle θ_c, given by,

$$\theta_c = \sin^{-1}(1/n)$$

will be trapped in the glass because of total internal reflection. Here n is the relative refractive index between the glass and the surrounding medium. This trapped light now moves from surface to surface laterally across the screen rather than through it. It is further scattered and finally, that which is not absorbed emerges from both the front and back surfaces of the screen. Less intensity will be lost by this mechanism if the scattering distribution is high gain rather than low gain as there is a larger contribution to the total intensity from large angles. This is particularly true near the edge of the screen where the angle between the extreme ray and the screen normal is greatest. However, the angle between the principal ray and the screen normal is reduced inside the glass because of refraction. All of the light trapped must be considered lost as it no longer can contribute to the image.

The intensity ratio between the light incident on the transparency and the screen is equal to the inverse square of the magnification. Thus if the screen can be made half as big, it will require only a fourth as much power to illuminate as the larger screen. This means bend angles will be smaller and less light will be internally trapped.

Any transparency can be thought of as having some average density. It has been shown that about 2/3 of the available intensity can be absorbed by the transparencies[26] causing them to heat up and possibly melt.

There are other reasons for poor screen illumination which depend on projector design and power as well as geometrical considerations[31-35,11]. The larger the angular size of the screen the greater the angle between the screen normal and the principal extreme rays. This means the principal axis of the distribution function varies over a wide range of angles across the surface being greatest at the edges of the screen; also, the bend angles are correspondingly greater. This is shown in Figure 6.

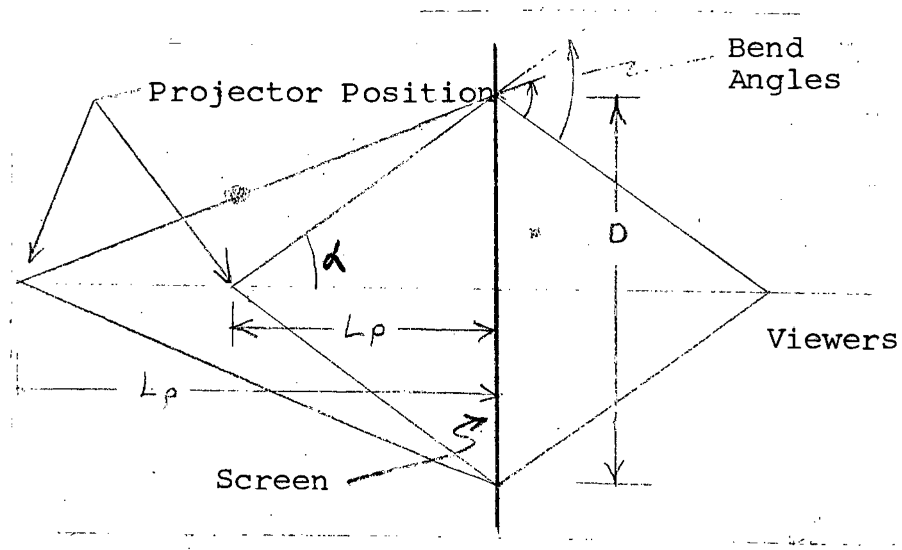


Figure 6. Effect of the Angular Size of the Screen on Bend Angle

This can come about by using short focal length projection lens, being closer to the screen, or by increasing the f/No. at which the projection lens is operating. The faster the lens the more light which can be projected on the screen, however this also increases the bend angle and may require a lower gain screen to maintain sufficient uniformity of illumination. Also the greater this angle the more reflection experienced at the surface. This is controlled only by the angle and the relative index of refraction between the screen and the surrounding medium.

The two curves of Figure 7 give the transmission coefficient as a function of angle of incidence through two air glass interfaces, for two orthogonal polarizations, e. g., N, normal to the screen and P parallel to the screen, as a function of the angle α.

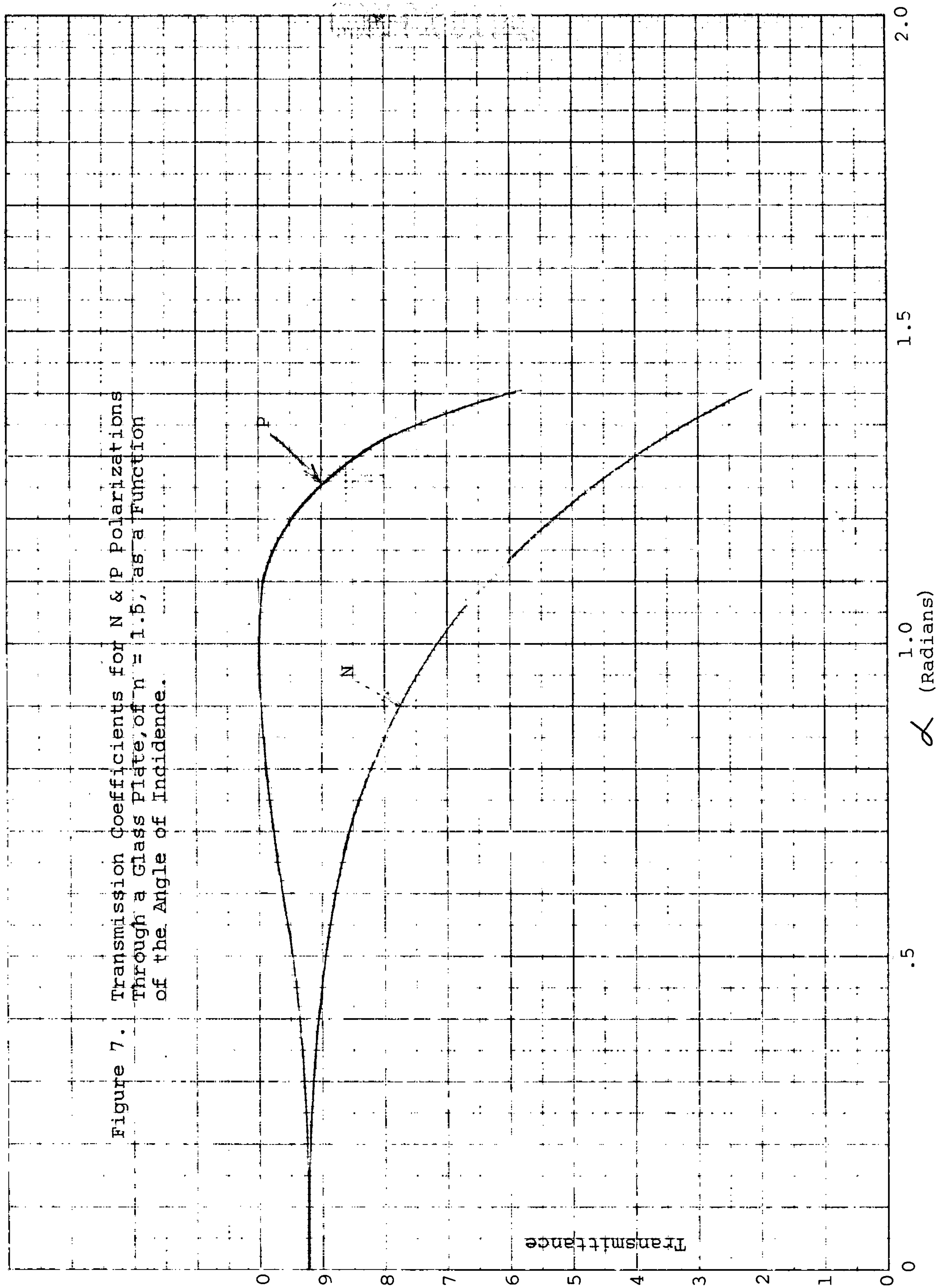


Figure 7. Transmission Coefficients for N & P Polarizations Through a Glass Plate, of n = 1.5, as a Function of the Angle of Incidence.

A constant fraction of power is lost at each air glass interface thus the total transmission coefficient is that for one interface raised to the kth power where k is the number of interfaces, in this case k is 2. It can be seen from the geometry of Figure 6 that α is defined by

$$\operatorname{Tan}\alpha = D/2\ L_p$$

where D is the screen diameter and L_p is the projection distance. As an example, these losses amount to about 10% for a screen 30 inches in diameter and a projection distance of 30 inches. The transmission coefficient changes from .92 for both polarizations at the center of the screen to a minimum of .82 and .98 for the N and P polarizations respectively at the edges of the screen. Even if the principal ray is normal to the screen there will still be a certain amount of angular reflection losses which arise because of the finite size of the projection lens. Light from all parts of the lens is used to form an image of a single point on the screen. Thus the angular cone of light from the lens should be considered rather than the principal ray, although little is lost in making such an approximation.

When all losses are considered in addition to backscatter losses and bend angle problems it is quite clear why so much projector power is required to give an acceptable display. Some projection systems even use more than one projector and "lace" the two displays together[36]. One must therefore optimize projection systems and projector power against screen gain and uniformity of screen brightness to obtain the most efficient screen at the lowest projector power. It is well known that many projection systems are literally burning up transparencies because of the need for a bright picture of uniform brightness over a wide range of bend angles. The most straightforward solution is to use the most efficient screens in very carefully optimized projection systems.

b. Sensitivity to Ambient Light

The sensitivity of the screen to ambient light is also very important and varies with the specific application[4, 37-40]. The more transmitting, i. e., the less diffusing, the screen the less sensitive it is to ambient light. This is important because in many applications the display is to be viewed with a certain amount of room light present. If the screen is highly transmitting the ambient light will pass through with very little being backscattered. However if the screen is highly diffusing it will also scatter the ambient light back to the observer and this will degrade the contrast of the image. Generally speaking, the greater the difference between the ambient intensity and the screen brightness the better will be the conditions for obtaining good quality on the projection screen. Whenever the ratio of these is less than 300:1, picture quality for normal density transparencies will begin to change. A decrease in this ratio to less than 30:1 results in almost total degradation of the screen image.

For these last conditions, one may rightly question the visual value of any display. This problem has been treated in detail using groups of observers and varying screen conditions[18,21,37]. One solution is to put a light absorbing material into the screen. The absorption tends to reduce the sensitivity to ambient light by absorbing a large fraction of it. However it also reduces the overall efficiency of the projection system by the same amount. Rear projection screens are also very sensitive to back illumination, a small amount of light can reduce the contrast appreciably.

c. Resolution

Resolution is one of the most important screen parameters as it limits the fineness of detail which can be usefully projected[10]. The most important factors limiting resolution are the size of the scattering irregularities and the thickness and scattering characteristics of the screen. Clearly, the thicker the screen the more spread out any point projected onto it will be by the time it reaches the viewing side. The amount of spreading is determined by the thickness and the scattering distribution of the material. Unfortunately no literature was found on the thickness effect and because of its importance it will be thoroughly treated in the theoretical phase of our work.

Any type of scattering centers will distort the light passing through them. This means that the larger the scattering centers the lower the inherent resolution of the screen. If glass spheres of a given diameter are used to produce the scattering then one could not expect any significant amount of resolution at that detail size or smaller. Another factor which reduces resolution is the light which is trapped in the screen. Because it moves across the screen and may emerge at a variety of places it will add light where there should be none and reduce the overall intensity of the image. Again the more diffusion the lower the contrast which can be expected. The theoretical aspects of resolution will be treated in detail later in this report.

A particularly effective way to obtain a fine grain, high resolution screen is to coat one side of a clear substrate, such as glass with a suitable diffusing layer. This layer may be a pigmented carrier consisting of resin and a solvent. The pigment may be any finely ground material having a different (generally higher) refractive index than the carrier. Ground glass in a plastic substrate is sometimes used.

d. Performance Ratings of Screens

Several authors[2,3,11] have proposed criteria for establishing a performance rating or figure-of-merit for rear projection screens. The shape factors previously described has been used while others have used the angle at which the maximum gain at $\theta = 0$ has fallen to half its value. Sachtleben[10] introduced a figure-of-merit based only on resolution. Some schemes are far more complex and involve the weighting of many selected parameters[11].

The most important aspect of the figure-of-merit approach is to use the one most important parameter such as efficiency, sensitivity to ambient light, resolution, or some weighted combination of parameters which show, for a given application, the relative quality of various types of screen materials. Because of the many different applications for rear projection screens it seems unreasonable to attempt to give a single number which can describe all possible material properties in sufficient detail with no regard to specific application.

It would be almost as questionable to assign a figure-of-merit to each of the parameters of a given screen material because requirements change with application and the parameters are by no means independent.

2. Other Approaches

Considerable effort has been directed to finding new techniques and different materials which do not directly depend on scattering for their light distribution properties[41]. This has been done to circumvent the inherent limitations of efficiency and uniform screen brightness set by light scattering materials.

Although very many ideas have been proposed and much work has gone into making them feasible, few rear projection screens reflect this effort. Some of the more promising techniques will be described in the following section.

a. Fresnel Screens

Fresnel screens, made by placing a diffusing screen and a Fresnel lens together have been investigated to determine their advantages and limitations[10]. It is possible to significantly increase the overall screen efficiency by directing the principal rays back toward the observer. This can be seen from Figure 8.

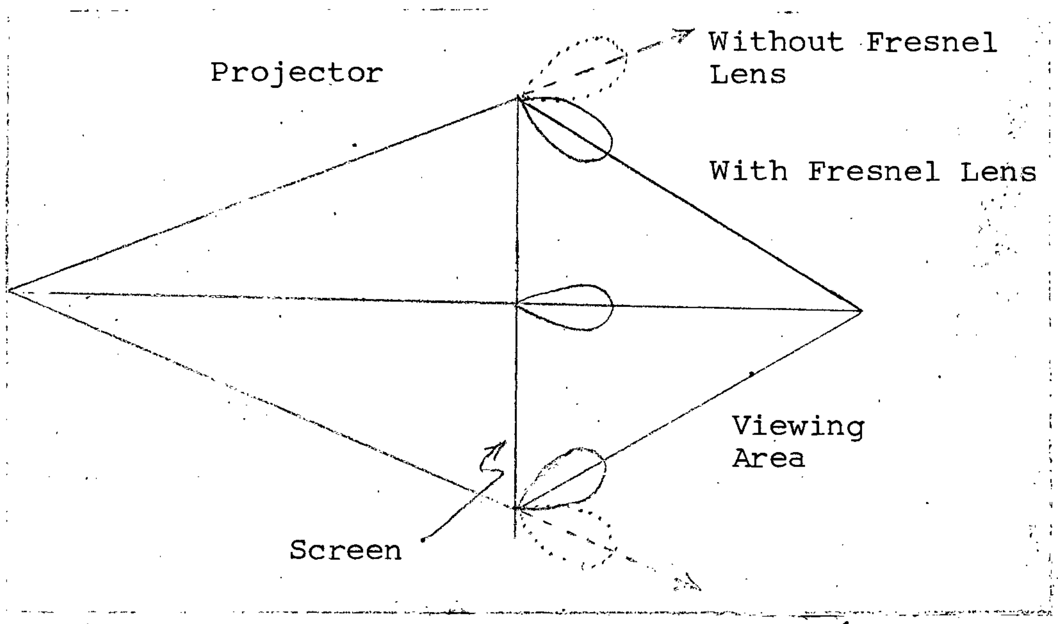


Figure 8. Redirection of the Principal Axes by Using a Fresnel Lens with a Standard Screen

Figure 9 gives gain curves for a diffusing screen with and without a Fresnel lens[42].

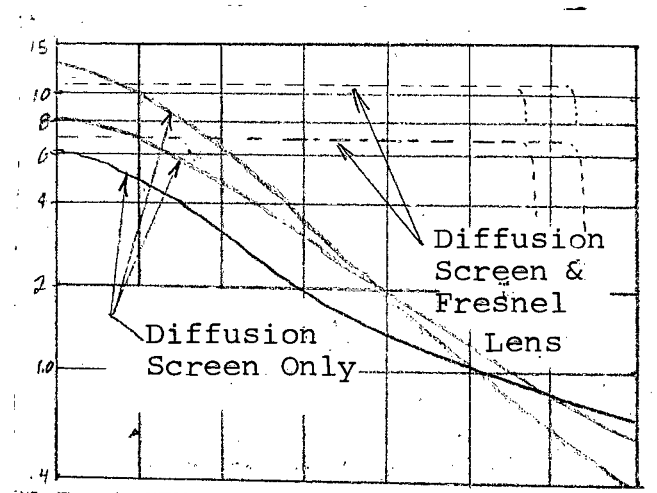


Figure 9. Relative Brightness of Diffusion and Combined Fresnel Diffusion Screens

A significant improvement can be seen by noting the increase of bend angles at which the screen can be viewed. This then permits the use of still higher gain, higher efficiency screens and at the same time it is possible to maintain a sufficiently uniform screen brightness. The use of Fresnel lenses also make it possible to use shorter projection distances and faster projection lenses. Also by allowing higher gain screens to be used the sensitivity of the displays to ambient light decreases.

This type of screen has found the most general use in camera view finders to make the image brighter. Otherwise these screens have seen only very limited use because of the difficulties and cost in making large high quality Fresnel lenses. They all seem to display an undesirable line structure. The detailed interactions of the lens grooves in the image even produce Moire fringes.

b. Lenticular Screens

Lenticular screens are made up of very small lenticules or lens-like elements, Figure 10.

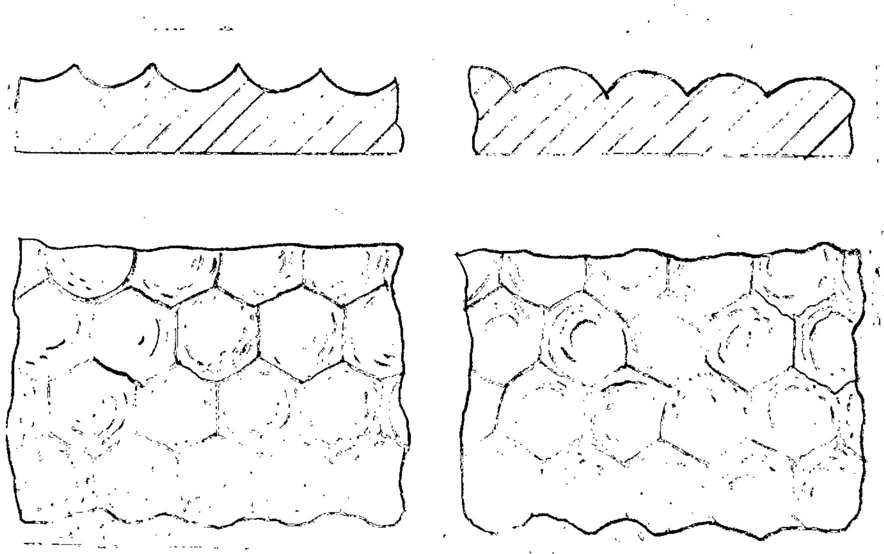


Figure 10. Some Possible Lenticular Configurations

Each receives a small portion of the light from the projector and re-distributes it to the viewers. These lenticular elements are efficient at distributing light through a given angle. In theory the lenticular screen is a logical development, but many serious problems of a practical nature remain to be solved before lenticulated screens can provide the smooth, even picture illumination of ordinary flat screens[12,42-44].

The chief cause of dissatisfaction with the lenticular screens available at the present time involves optical difficulties created when the several lenticulated panels are joined together to produce screens of the required large sizes.

Because each tiny lenticule directs light quite differently than does a plane surface and since the high axial gain of lenticular screens (nearly twice that of perforated matte screens) depends upon the optical functioning of the individual lenticules, any slight interruptions in their continuity or minor alterations in their depth and form exert a profound effect upon their transmission characteristics.

Seams where the panels are joined show up as black or gray lines and the illuminated surface of a lenticular screen seldom looks uniformly bright but is marred by the slightly differences in the transmittances of the several panels. Differences of 5% are easily visible, while differences of 10%-20% completely spoil the display.

The cost of lenticular screens are also high inasmuch as the manufacturing process requires several types of large embassing equipment. In some applications lenticular screens are used in conjunction with standard diffusing screens.

c. Fiber Optics Screens

Very little has been reported on the application of fiber optics to rear projection screens. This is primarily due to the very high production costs.

So far the screens made of optical fibers do not give a photometric performance comparable to commercial screen materials used with a Fresnel lens. However they are reasonably similar when no additional lens is used. The one extensive investigation[10] describes screens which have a substantially uniform brightness out to a viewing angle of 45°.

The limit of resolution of these screens from consideration of fiber diameter alone is about 100 lines/mm. However because of other considerations it has only been possible to realize from 40 to 60 lines/mm.

Several types of fiber configurations were investigated in this study[10]:

1. Single cladded fiber.
2. Double cladded fiber in which the second cladding was highly absorbing.
3. Cladded fibers which had hollow ends.
4. Cladded fibers with diffusing material in the ends of the fibers.
5. Flat ended bundles with etched surfaces.

A 7½" square experimental screen was constructed from 10 smaller segments to determine how large the constituent fiber optics segments could be made, the visible effects of such construction on the image, and the practical minimum thickness for these screens. Perceptable discontinuity could be seen and was attributed to a discontinuous jump in the fiber orientation at the boundaries. In addition, the boundaries themselves create a sharp line.

An outstanding defect in the performance of the large fiber optics screen was its low inherent contrast at large viewing angles. The contrast was good when the screen was viewed normally, but dropped severely as the viewing angle increased. The reasons for this are understood. The chief contributors to low inherent contrast are: (1) a lack of absorption of the light that escaped from the fibers into the cladding and (2) the large thickness of the supporting glass plate, which helps to spread any light returned to the fibers from its outside surface.

It is important to note that the use of a second absorbing cladding would not entirely solve the problem of low inherent contrast if the fiber optics structure is supported on a glass plate. This is because a considerable fraction of the light from the fibers is confined to the fiber cores until it reaches the supporting plate, after which it may diverge inside the plate at angles to the screen normal as great as $\cos^{-1} n_c/n_f$ where n_c = refractive index of the first cladding, n_f = refractive index of the fiber core. This also assures the glass plate to be of refractive index n_f. By keeping the ratio n_c/n_f as large as possible, consistent with the need to confine light from the projector to the fibers, the angle $\cos^{-1} n_c/n_f$ may be kept at a minimum. The escaped light scattered by the supporting plate will be absorbed by the second cladding. Thus, some control of inherent contrast may be maintained by choosing cores and cladding with the proper refractive indexes.

Corning Glass Works has recently assembled an octogonal 12" diameter fiber optics plate 1" thick with a transmission of 50%. It has a numerical aperture of 1.1 which gives it an extremely large viewing angle. It is made up of cladded solid core fibers measuring 7 microns in diameter.

Although much work has been done in the field of rear projection the results of the literature search indicate a general lack of analytical descriptions for important rear projection system parameters. There are many commercial screen materials available but it seems likely that few if any have been designed from basic theoretical considerations but rather have been developed on a best estimate trial and error basis. It is therefore difficult to access the ultimate quality of such materials or systems compared to some ideal standard. For example, from a comparison between theoretical losses and actual losses, one can infer the quality of a given real system and also learn where and why the major differences occur. As important as resolution is to a projection system almost nothing has been published on the influence of stray light or of the light trapped by internal reflections. Nothing was found on the limiting effects of thickness and scattering.

It is essential to be able to interpret operational performance into system requirements and to investigate the sometimes severe limitations imposed on a projection system by a single performance requirement. For example, reducing the screen sensitivity to ambient light may cause the overall screen efficiency to fall by an order of magnitude. If this is realized before committments on a system are made, a more practical set of performance requirements can be established.

All of this is important if one is to optimize a given display system. This is difficult to do because of the many interrelated parameters and the lengthy calculations required. Surely this is done to an extent but because of the lack of analytical descriptions it seems unlikely it has been done thoroughly.

During the theoretical and experimental phases of this program we hope to clarify many of these questions by putting the theory of rear projection systems on a more solid analytical foundation. In doing so, we expect to be able, by utilizing computer techniques to investigate these relationships and optimize materials and projection systems to a set of performance specifications and to show the relative influence of each requirement on the system. In light of these results it seems we can materially contribute to a better understanding of rear projection screens and systems and at the same time better evaluate the applicability of CGW materials for projection screens.

References

(1) J. H. O. Harries, "Sunflower Optics: A New Concept in Color TV Display," Electronics, 35, 33 (1962).

(2) P. Vlahos, "Selection and Specification of Rear-Projection Screens," J. SMPTE, 70, 89 (1961).

(3) A. J. Hill, "Analysis of Background Process Screens", J. SMPTE, 66, 393 (1957).

(4) J. F. Dreyer, "Operational Characteristics of Rear Projection," J. SMPTE, 68, 521 (1959).

(5) E. W. D'Arcy and G. Lessman, "Objective Evaluation of Projection Screens," J. SMPTE, 61, 702 (1953).

(6) F. B. Berger, "Characteristics of Motion Picture and Television Screens," J. SMPTE, 55, 131 (1950).

(7) "You Want to Project a Good Picture? Proper Screen Selection, Servicing is a Must", International Projectionist, 36, 8 (1961).

(8) H. McG. Ross, "High-Diffusion Screens for Process Projection," British Kinematography, 16, 189 (1950).

(9) Y. G. Hurd, "Some Comments on Procedures Used to Compare Theater Screens," J.SMPTE, 66, 340 (1957).

(10) L. T. Sachtleben, "High Resolution Display Media," ASTIA Report 277 746, May 7, 1962.

(11) A. J. Hill, "A First-Order Theory of Diffuse Reflecting and Transmitting Surfaces," J. SMPTE, 61, 19 (1953).

(12) G. Schwesinger, "Proposal of a Performance Rating for Projection Screens," J. SMPTE, 63, 9 (1954).

(13) H. C. Van de Hulst, Light Scattering by Small Particles, (John Wiley & Sons, New York, 1957).

(14) A. P. Prishivalko,"Study of Light Scattering From Large Highly Absorbing Spherical Particles,"Optics & Spectroscorpy, 14, 139 (1963).

(15) L. M. Romanova,"Radiation Field in Plane Layers of a Turbid Medium With Highly Anisotropic Scattering,"Optics and Spectroscopy, 14, 135 (1963).

(16) A. V. Shatilov,"On the Scattering of Light by Dielectric Ellipsoids Comparable with the Wavelength," Optics & Spectroscopy, 9, 123 (1960).

(17) A. V. Shatilov, "Anomalous Scattering as a Case of Scattering by a System of Particles," Optics & Spectroscopy, 13, 412 (1962).

(18) B. O'Brien and C. M. Tuttle, "An Experimental Investigation of Projection Screen Brightness," J. SMPE, 44, 505 (1936).

(19) L. Knopp,"Symposium on Screen Viewing," Trans. Illum. Eng. Soc. (London), 21, 199, (1956).

(20) E. M. Lowry, "Screen Brightness and the Visual Functions," J. SMPE, 44, 490 (1936).

(21) D. Jameson and L. M. Hurvich, "Complexities of Perceived Brightness," Science, 133, 174 (1961).

(22) R. G. Hopkinson, "Magnitude of Discomfort Caused by High Brightness," Nature, 181, 1076 (1958).

(23) O. Bryngdahl, "Linear Model for Visual Transfer Characteristics in the Mesopic Region--Response/Stimulus Peak-to-Peak Measurements of Spatial Sine-Wave Patterns," Optica Acta, 12, 1 (1965).

(24) M. R. Null, W. W. Lozier, and D. B. Joy, "The Color of Light on the Projection Screen," J. SMPTE, 50, 219 (1942).

(25) H. Hartridge, "The Optimum Conditions for Viewing by Projection," Photographic Journal, 115, 81 (1958).

(26) R. A. Mitchell, "Color Factors in Projection Illumination," International Projectionist, 36, 4, (1961).

(27) K. Shibata, Carnegie Institution of Washington, Year Book No. 55, 252 (1956).

(28) R. Ollerenshaw, "Design for Projection: A Study of Legibility," Photographic Journal, 119, 41 (1962).

(29) "Basic Screen - Light Terms", International Projectionist, 33, 5 (1958).

(30) K. A. Staley,"Fundamentals of Light and Lighting," G. E., August, 1960.

(31) B. S. Lee, "The Design of Projection Systems," Phot. Eng., 1, 94 (1905).

(32) A. A. Cook, "A Review of Projector and Screen Characteristics and Their Effects Upon Screen Brightness," J. SMPE, 44, 522 (1936).

(33) F. J. Kolb, Jr., "Specifying and Measuring the Brightness of Motion Picture Screens," J. SMPTE, 61, 533 (1953).

(34) A. J. Hill, "Averaging Screen-Illumination Readings," J. SMPTE, 67, 144 (1958).

(35) H. Hartridge, "The Optimum Conditions for Viewing by Projection: Part II," Photographic Journal, 100, 81 (1960).

(36) A. A. Gillespie, "Laced Process--A New System of Rear-Projection Process," J. SMPTE, 73, 947 (1964).

(37) R. L. Estes, "Effects of Stray Light on the Quality of Projected Pictures at Various Levels of Screen Brightness," J. SMPTE, 61, 257 (1953).

(38) M. Denson, "Projection Techniques at the World's Fair," J. SMPTE, 73, 507 (1964).

(39) National Boat Show, New York, 1964, Rear Screen Presentation at the Coliseum in New York.

(40) S. A. Francis, "Lighting, Building Design, and Human Factors in Systems Engineering," Symposium on the Illumination & Visibility of Radar and Sonar Displays.

(41) R. Henkel, Electronic News, March 1, 1965.

(42) C. R. Daily, "High Efficiency Rear-Projection Screens," J. SMPTE, 65, 470 (1956).

(43) R. A. Mitchell, "Are Lenticulated Screens Practical?," International Projectionist, 33, 5 (1958).

(44) G. Schwesinger, "Experiments with Lenticulated Rear Projection Screens," Phot. Eng., 5, 172 (1954).

B. Patent Literature on Rear Projection Screens

A search of both the domestic and foreign patent literature from 1945 to date has been made. The patents obtained include 37 U. S., 8 British, and 1 each Australian and French making a total of 47. However of these only 29 are directly related to rear projection screens per se and even then a single idea may be covered by several patents. Very little is presented on the control of light diffusion, nor was any mention made of using optical fibers as a screen material.

For clarity the patent literature will be discussed under the following classifications:

1. General lenticular screens.
2. Fresnel screens.
3. Dynamic screens.
4. Hybrid screens.
5. Unrelated screen patents.

1. Lenticular Screens

A lenticular screen in its broadest meaning is one which has some type of non-planar surface characteristics. These generally have some type of hemispherical, beaded, ground, or embossed surface with any number of different geometrical shapes and/or patterns.

A type of rear projection screen is described by E. W. Kellogg[1] which distributes light only through a given angle by using two sets of surface corrugations at right angles to one another and both on the viewing side of the screen, Figure la.

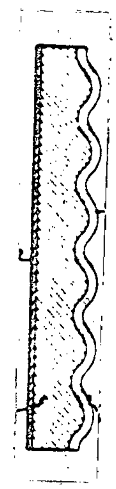


Figure 1a. Corrugated Viewing Screen

Further, by the use of molded annular corrugations on the projection side of the screen in the form of a large Fresnel lens, Figure 1b, the divergence of the light from the projector may be offset.

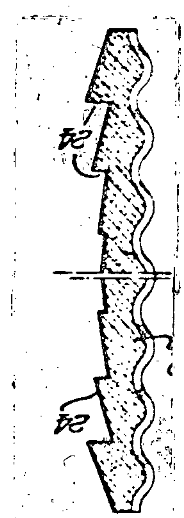


Figure 1b. Fresnel Surface used with a Corrugated Viewing Screen

B. E. Luboshez[2,3] and A. Bowen[4] discuss the advantages of using two orthogonal sets of cylinder lenses and masks which give a screen that restricts the light to certain angles in the vertical and horizontal direction and which is very insensitive to ambient light, Figure 2.

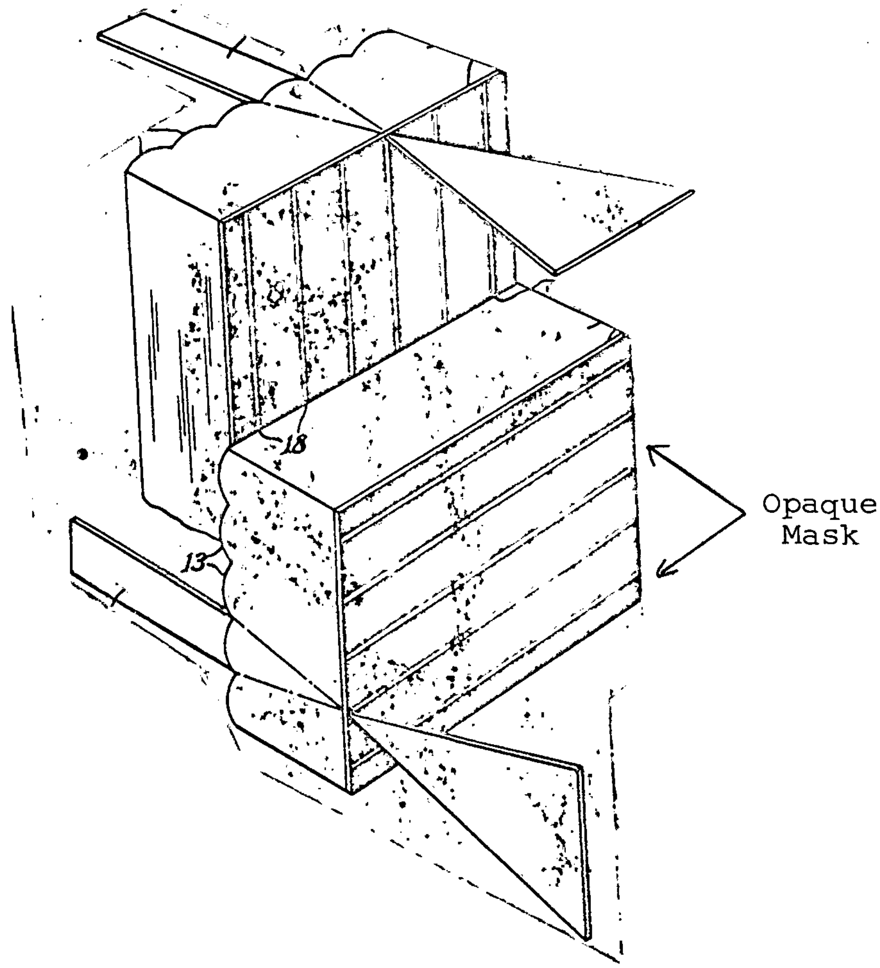


Figure 2. Light Distribution from Orthogonal Cylindrical Lenses

Anisotropic screens can be assembled by using two different focal length cylinder lenses. A method of producing the cylinder lenses is also discussed.

A patent by H. A. Thompson[5] utilizes this masking effect to decrease the sensitivity of a rear projection screen to ambient light. Efficiency is increased by using very small, highly reflective parabolic depressions in the screen on the projector side which may or may not be capped with small lenticules on the viewing side which have a focus in common with its respective parabolic element, Figure 3.

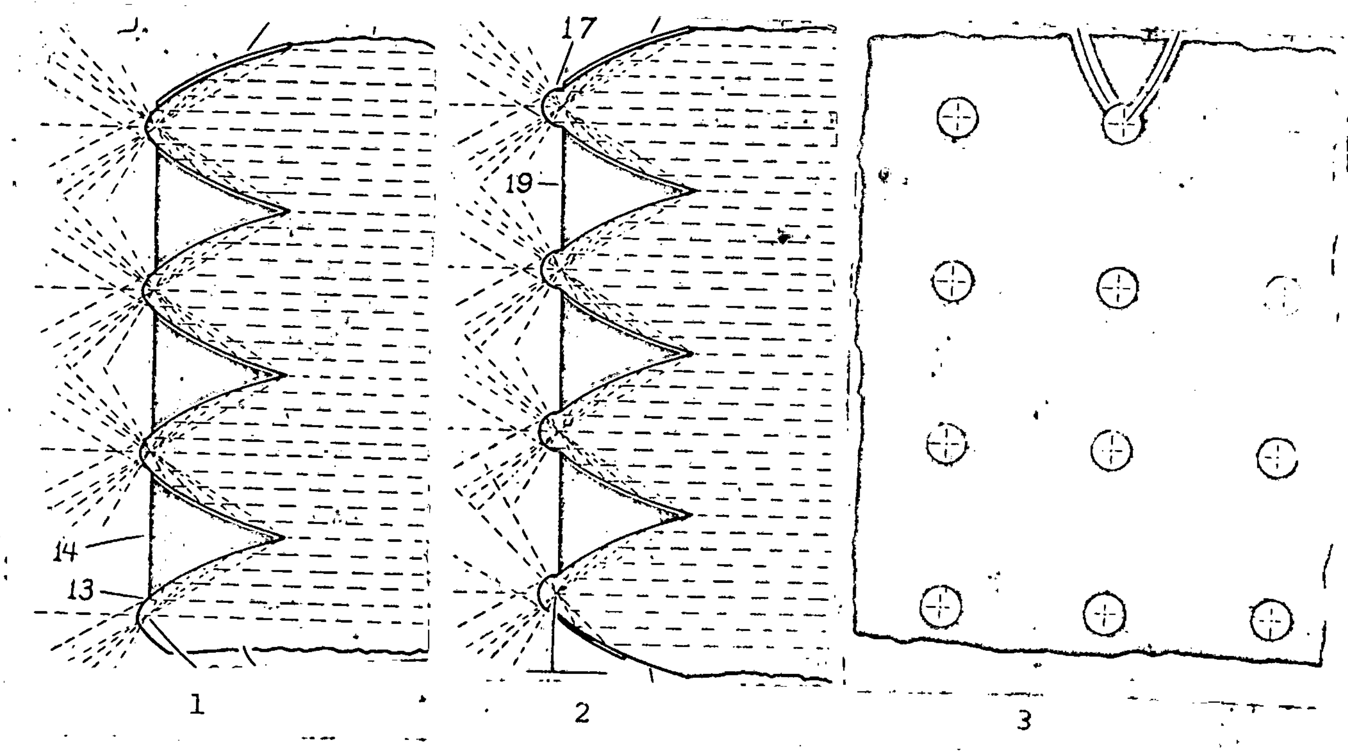


Figure 3. Light Distribution from Reflecting Parabolic Elements (1) and with Associated Lenticular Caps (2). Front View of Screens Show Coated Area.

The area of the lenticule is much smaller than the area of the corresponding paraboloid hence all the area exterior to the lenticule can be coated with a light absorbing material to decrease the sensitivity to ambient light without decreasing its efficiency.

The object of a patent by G. Schwesinger[6] is a lenticulated rear projection screen whose scattering characteristics are strictly controlled through optical design rather than being dependent upon uncontrolled scattering and refraction by random surface irregularities. This is claimed to circumvent the physical incompatibility requirement of having a screen which is highly efficient with a low surface reflection and which spreads the transmitted light uniformly over a certain wide range of viewing angles. The geometry of the lenticular elements is computed theoretically. A theoretical treatment of required surface geometry is also given by H. R. Schulz[7] in describing the required cylindrical surface to remove the line structure from television pictures.

A straightforward way of producing a lenticular surface following J. S. Thompson et al[8] and H. C. Staehle et al[9] is to form it from plastic in a lenticular mold, or by cementing small lenticular elements to the surface of a clear or diffusing screen as patented by P. C. Robinson[10].

Another type of lenticular screen is outlined by E. G. Beard[11] which consists of several sets of concentric rings cut into a plastic material and the center of each set being displaced from that of any other of the sets. The surface of the screen may also be roughened to increase its scattering properties.

A lenticular screen has been patented in England by Phillips Electrical Limited[12] which rather than use strictly circular rings make each ring vary laterally in a sinusoidal pattern, Figure 4.

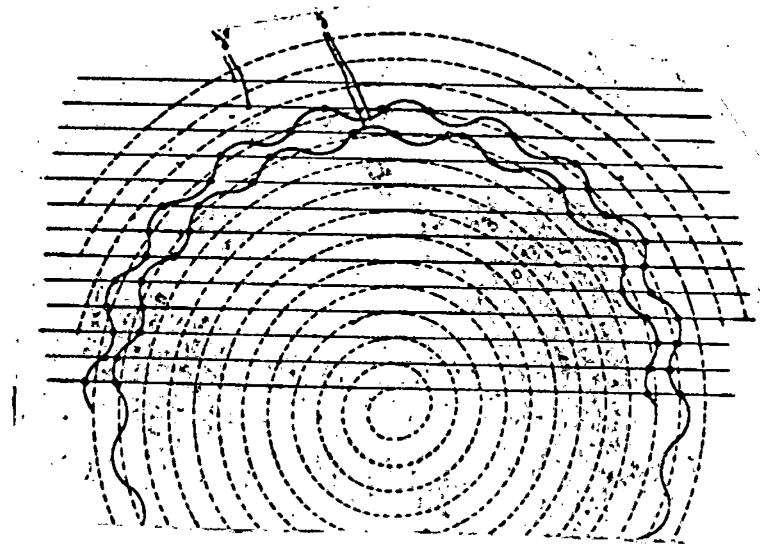


Figure 4. Laterally Varying Rings cut into a Screen's Surface

A completely different type of surface treatment is proposed by B. V. Bowden[13] where a mixture of powdered glass and a low viscosity plastic is sprayed onto some kind of structural backing. A screen can be made insensitive to ambient light by forming some type of sharp conical depression in the surface. Light incident on this type of structure is eventually all transmitted as it moves further down the cone, Figure 5.

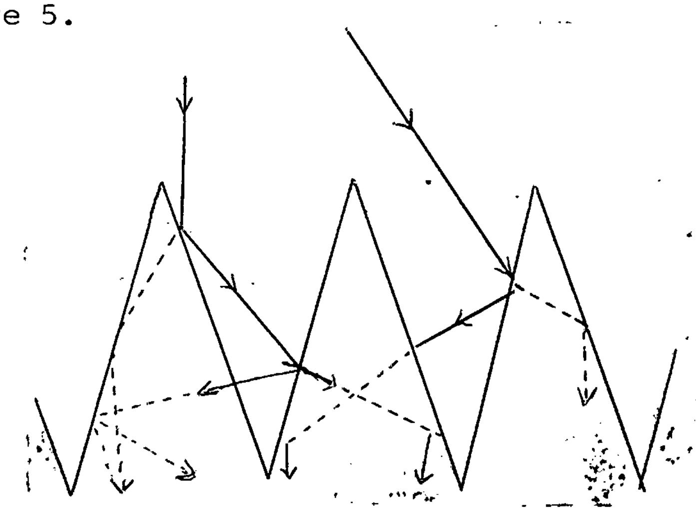


Figure 5. The Trapping of Light in Conical Depressions

This is the essence of a patent by P. J. Corso et al[14]. If both sides have this configuration more projection light also passes through the surface and hence through the screen, nothing is mentioned about its effect on resolution.

It can be shown that any ray of light, which impinges upon a cube corner reflector successively strikes all three faces and is set back toward the source. If the cube corner is very small the light ray will return exactly to the point from which it came. Hence, since the pupils of the eye do not radiate light the screen will appear dark. A patent by R. T. Erban[15] suggests the use of cube corner surfaces to be placed on the viewing side of a projection screen to reduce its sensitivity to ambient light.

A more mechanical technique is suggested in a patent by I. Goodbar[16]. Two sets of louvers, normal to each other, are placed near the screen surface and are used to limit the angles at which the screen can be viewed and the angles at which ambient light can reflect off from it to the viewer.

R. N. Rhodes et al[17] propose an obvious technique of putting an antireflection coating on the surface then some type of cross-mesh screen, again to limit the angles at which reflection can occur. The antireflection works reasonably well at near normal incidence and the cross-mesh becomes more efficient at the larger angles where the coating does little or nothing.

This group of patents are also concerned with reducing the amount of trapped light between the two surfaces because of total internal reflection. Light scattered at angles greater than the critical angle for total internal reflection will be trapped and move across the screen rather than through it. This reduces the contrast of surrounding detail and is therefore undesirable. J. S. Jacobson[18] suggests using modified sinusoidal lenticules. These are made so that the portions of each sine curve, essentially parallel to the surface of the screen, are omitted. Almost any type of lenticular surface has the property of limiting the sideways diffusion of light.

A more novel way is disclosed in a patent by G. L. Fredendall[19] to put very small metallic plates in a liquid screen material. These are aligned using a magnetic field and the screen material is then allowed to set or harden. These act somewhat as fibers to prevent the lateral diffusion of light in the screen.

2. Fresnel Screens

A Fresnel screen or lens consist of a series of concentric stepped rings, each one being a section of a convex surface, Figure 6.

Ordinary Lens   Fresnel Lens

Figure 6. Concept of the Fresnel Lens

The combined effect of all the rings is the same as that of a single lens of normal shape with the same diameter and curvature.

A special class of lenticular screens utilizing these Fresnel surfaces of one type or other are used to compensate for the divergence of the light from the projection lens, the effect of using such a lens is shown in Figure 7, where the main propagation lobe is turned toward the viewing area.

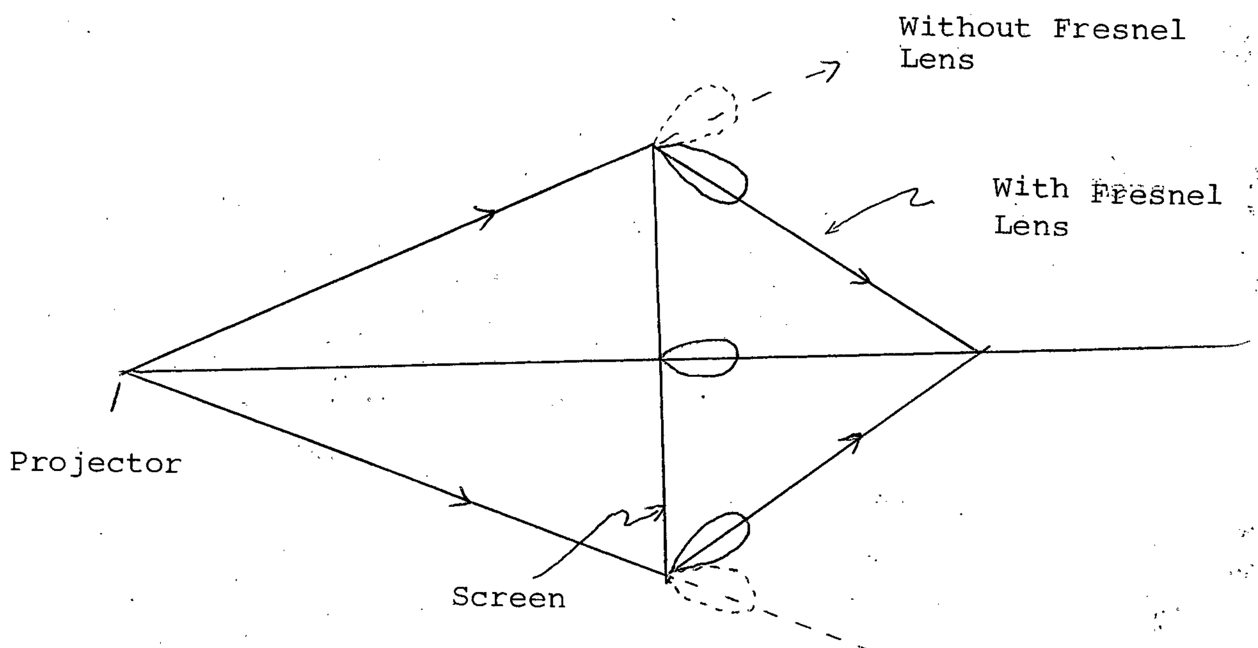


Figure 7. The Influence of a Fresnel Surface on the Light Through a Screen

They can also be used to redirect light from a source to an observer who is at a different level, Figure 8. Both of these advantages have been combined in a patent by G. J. Siezen[20].

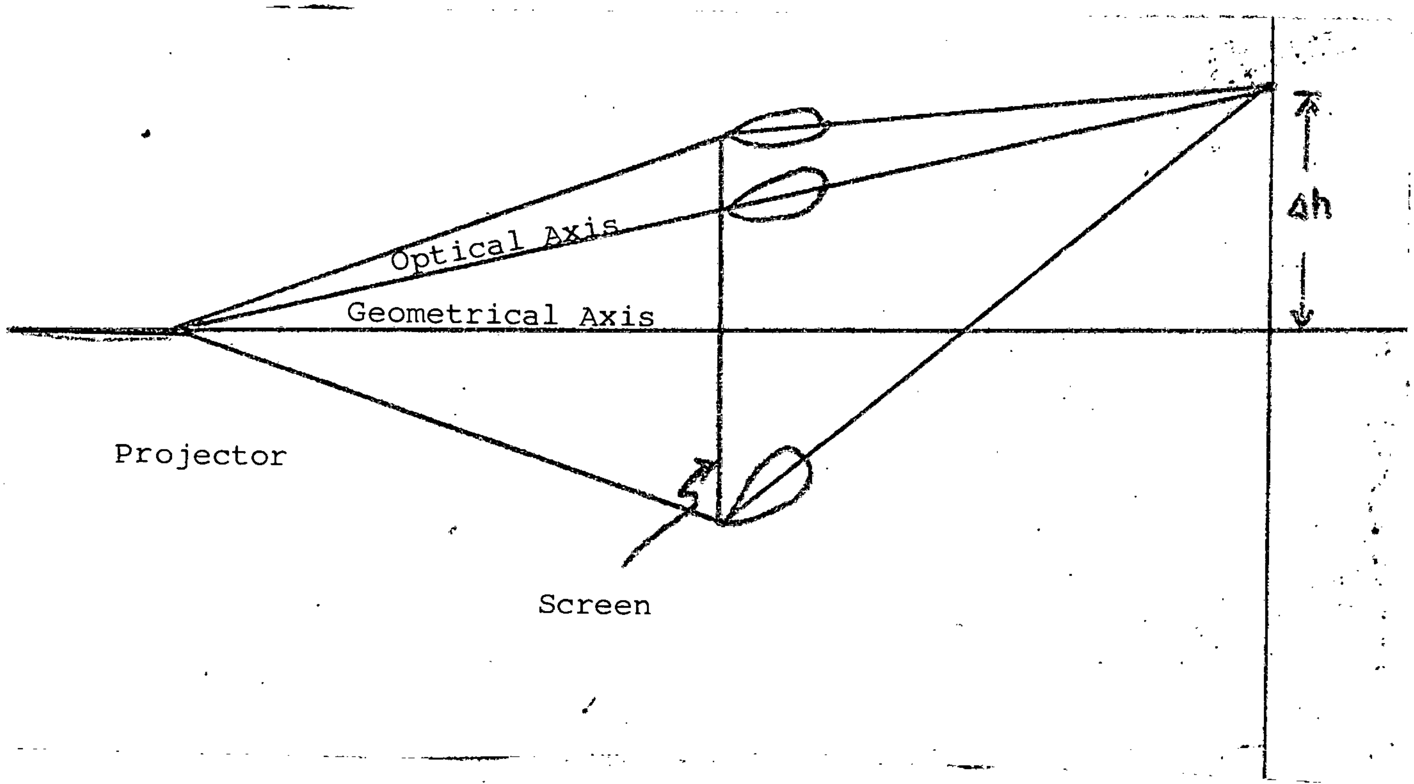


Figure 8. A Fresnel Surface used to Compensate for the Observer and Screen being at Different Levels

I. G. Maloff[21,22] suggests using one Fresnel surface and one cylindrical lenticular surface to give the desired light distribution. This disclosure includes screens which are transparent, i. e., no scattering per se, and others which have a diffusing layer between the two lenticular surfaces. As previously mentioned, E. W. Kellogg[1] also utilizes a combination of a Fresnel surface and other lenticular elements for fear projection screens.

Still another patent[23] uses a Fresnel surface toward the projector and a diffusing surface facing the viewers.

3. Dynamic Screens

One of the more novel screens is described in three patents by R. T. Erban[24-26]. Here two Fresnel screens or a Fresnel screen and a lenticular screen are superimposed and moved relative to each other more rapidly than the eye can perceive the motion, Figure 9, thus the term dynamic screens.

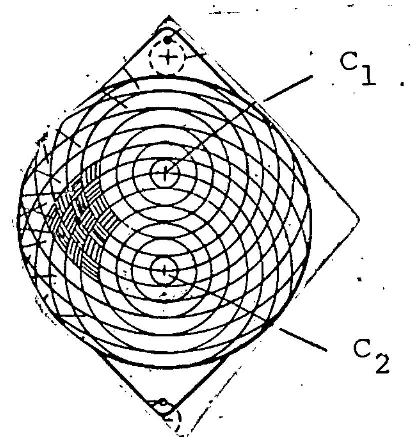


Figure 9. A Dynamic Screen Showing Their Two Respective Centers

This has several advantages, the most important of which is better coverage of the audience with the projected light. The screen may be operated to give any degree of anisotropic illumination while having an absence of the degrading line structure of the Fresnel and lenticular surfaces. The advantages of dynamic scanning of the screen have been presented in patents by J. S. Jacobson[18] and R. T. Erban[24-26]. The last referenced patent by Erban goes into great detail on scanning techniques whereby rear projection screens can be moved relative to the image to soften the effect of the screen surface structure. Here the scanning mechanisms are patented rather than any single type of screen.

4. Hybrid Screens

Some inventions attempt to combine the advantages of both front and rear projection screens and are therefore called hybrid screens. A patent by W. S. Miller[27] uses a lenticular surface to reflect a projected image into a viewing area. The distortion is compensated for by using a two mirror system, Figure 10; however some depth effects are still present. This also has the advantage of reflecting a good portion of the ambient light out of the viewing area.

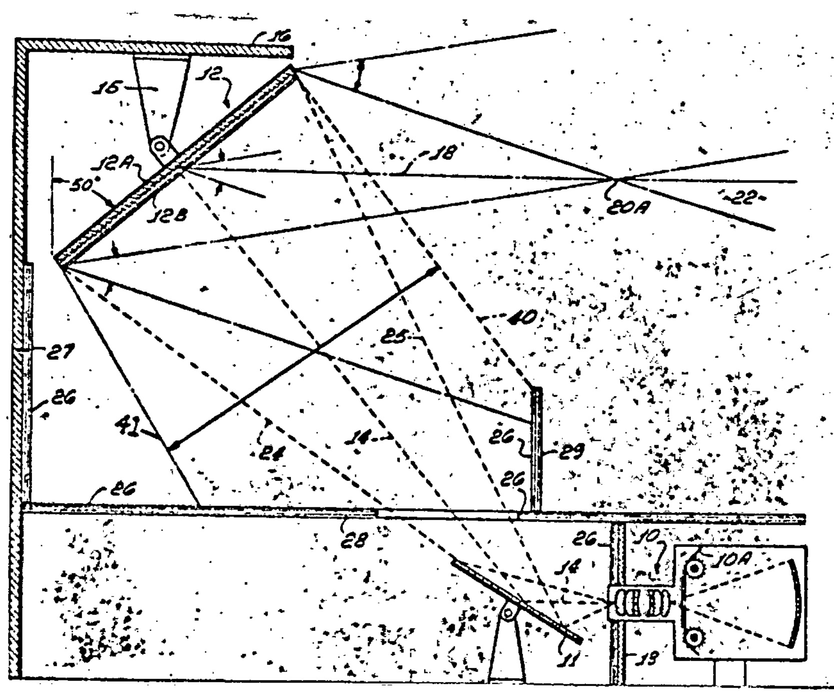


Figure 10. One Type of Hybrid Screen

A better system has been patented by A. H. J. De Lassus St. Genies[28]. The screen consists of a thin layer of surfaces inclined at 45° to the surface of the screen. One side of the surfaces is highly reflective and the other is coated with a light scattering material, Figure 11.

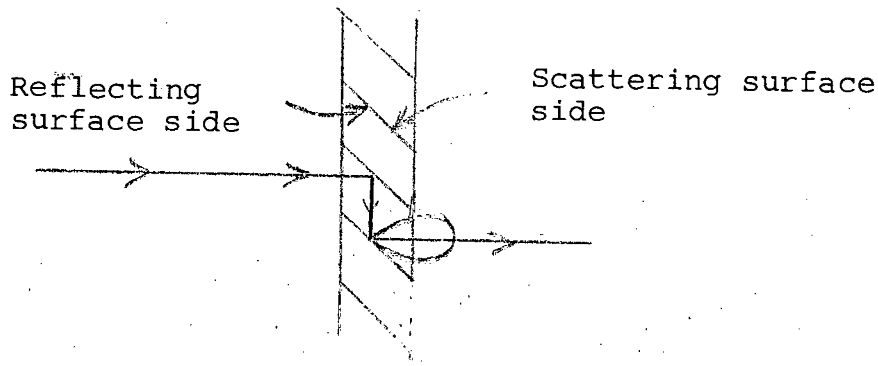


Figure 11. A Novel Hybrid Screen

Light incident from the back of the screen reflects from the first surfaces and is diffused into the viewing area by the second. The inclination of the surfaces can also be changed with increasing distance from the center of the screen which helps considerably in keeping it uniformly illuminated, i. e., it behaves much like a Fresnel screen. It also has the inherent high efficiencies of front projection screens and further the image detail is not disected by lenticules or fiber elements. Under normal viewing conditions no depth effects are observable because of the thinness of the screen.

5. Unrelated Patents

Several patents related to rear projection screens but were concerned with a screen on which a three-dimensional effect could be achieved by using special projection techniques[29-32].

Some related to frames and screen supports for portable projection units[33-37]. Others combined the projector and screen into a single housing[38]. Various ways of shielding rear projection screens out-of-doors from strong ambient light are also given[39-41].

Patents have been granted for specially coated projection screens to compensate for uneven illumination of the screen by the projector[39-42], for use at drive-in theaters[43], as inflatable buoyant display balloons with the projector on the inside[44], or for screens integrated with a theatrical stage to maintain[45] an effective presentation of both real and projected material. Another[46] describes a focusing viewer using a lens as a ground glass screen. One disclosure describes a clever way to make animated signs whereby a lens is segmented and rearranged randomly. A stencil placed behind the lens elements can be made to scintillate with ever changing color combinations by scanning colored slits across their common focal plane[47].

Of the patents reviewed almost all which deal directly with rear projection screens are concerned with some type of lenticular screen configuration. Of primary interest is the Fresnel screen made by using a Fresnel lens in conjunction with a regular diffusing screen or other lenticular elements. Many techniques for the production of the lenticules, grooves, and corrugations appear in the patent literature along with methods for molding spherical or hemispherical surface features using glass or plastic beads.

Very few theoretical developments were given to establish a general set of relations for lenticular materials. In view of the contents of the patents covered, there seems to be little similarity between the materials discussed and CGW materials which we will be investigating.

References

(1) E. W. Kellogg, Rear-Projection Screen, U. S. Patent No. 2,480,031, August 23, 1949.

(2) B. E. Luboshez, Projection Screen, U. S. Patent No. 2,618,198, November 18, 1952.

(3) B. E. Luboshez, Device for Making Projection Screens, U. S. Patent No. 2,694,226, November 16, 1954.

(4) A. Bowen, Improvements in Projection Screens, British Patent No. 570,691, July 18, 1945.

(5) H. A. Thompson, Jr., Back-Lighted Projection Screens, U. S. Patent No. 2,738,706, March 20, 1956.

(6) G. Schwesinger, Lenticulated Rear Projection Screen, U. S. Patent No. 2,870,673, January 27, 1959.

(7) H. R. Schulz, Device for the Removal of the Line Structure of Television Pictures, U. S. Patent No. 3,145,264, August 18, 1964.

(8) J. S. Thompson, et al, Backlit Projection Screen, U. S. Patent No. 3,173,332, March 16, 1965.

(9) H. C. Staehle, E. E. Jelley, and D. E. Bennett, Jr., Rear Projection Screen, French Patent No. 959,731, April 3, 1950.

(10) P. C. Robison, Backlit Projection Screen, U. S. Patent No. 3,183,775, May 18, 1965.

(11) E. G. Beard, Projection Screen, U. S. Patent No. 2,934,998, May 3, 1960.

(12) Philips Electrical Limited, Improvements in or Relating to Optical Projection Screens, British Patent No. 680,522, October 8,1952.

(13) B. V. Bowden, Improvements in or Relating to Translucent Cinematograph Projection Screens, British Patent No. 676,315, July 23, 1952.

(14) P. J. Corso et al, Outdoor Picture Projection Screen Apparatus, U. S. Patent No. 2,651,234, September 8, 1953.

(15) R. T. Erban, Optical Screen, U. S. Patent No. 3,057,256, October 9, 1962.

(16) I. Goodbar, Projection Screen, U. S. Patent No. 2,884,834, May 5, 1959.

(17) R. N. Rhodes et al, Light Reflection Reducing Device, U. S. Patent No. 2,977,412, March 28, 1961.

(18) J. S. Jacobson, Picture Projection Screens, U. S. Patent No. 2,948,187, August 9, 1960.

(19) G. L. Fredendall, Viewing Screen, U. S. Patent No. 2,584,441, February 5, 1952.

(20) G. J. Siezen, Screen Comprising a Fresnel Surface and Projection Device Comprising Such a Screen, U. S. Patent No. 2,596,049, May 6, 1952.

(21) I. G. Maloff, Rear Projection Viewing Screen, U. S. Patent No. 2,529,701, November 14, 1950.

(22) I. G. Maloff, Rear Projection Viewing Screen, U. S. Patent No. 2,726,573, December 13, 1955.

(23) Cinema-Television Limited, and T. M. C. Lance, Improvements in or Relating to Screens for Viewing Projected Optical Images, British Patent No. 596,813, January 12, 1948.

(24) R. T. Erban, Kinoptic Device, U. S. Patent No. 2,588,373, March 11, 1952.

(25) R. T. Erban, Kinoptic Devices, U. S. Patent No. 2,780,136, February 5, 1957.

(26) R. T. Erban, Projection Screen, U. S. Patent No. 3,125,927, March 24, 1964.

(27) W. S. Miller, Improvements in or Relating to Projection Systems, British Patent No. 966,228, August 6, 1964.

(28) A. H. J. De Lassus St. Genies, Projection Screen with Reflex Light-Transmission, U. S. Patent No. 2,931,269, April 5, 1960.

(29) A. E. De Los Monteros, Apparatus for Projecting and Viewing Images with Depth Effects, U. S. Patent No. 2,468,046, April 26, 1949.

(30) E. J. Pareto, Stereoscopic Picture Projection and Viewing Means for Theatres, U. S. Patent No. 3,063,333, November 13, 1962.

(31) F. Pohl, Optical System for Viewing Pictures, U. S. Patent No. 2,884,833, May 5, 1959.

(32) M. P. Rehorn, Stereoscopic Viewing Method and Apparatus, U. S. Patent No. 2,631,496, March 17, 1953.

(33) R. G. Allen, Projection Screen Device with Vertically Adjustable Detachable Legs, U. S. Patent No. 3,134,299, May 26, 1964.

(34) G. L. Moutray, Tri-Fold Rear Projection Screen, U. S. Patent No. 3,191,492, June 29, 1965.

(35) J. L. Stableford, Rear Projection Screen Unit for Picture Projections, U. S. Patent No. 2,617,328, November 11, 1952.

(36) Citizens of the City of Manchester, England, An Optical Rear Projection Screen Unit, British Patent No. 672,802, May 28, 1952.

(37) J. M. G. Finlay, Improvements Relating to Rear Projection Screens, Australia Patent No. 208,751, June 12, 1957.

(38) M. N. Hillyer et al, Viewing Screen Assembly for Movie Projectors, U. S. Patent No. 3,025,757, March 20, 1962.

(39) B. M. Bodde, Translucent Screen, U. S. Patent No. 2,368,099, January 30, 1945.

(40) P. J. Corso, Outdoor Motion Picture Projection Apparatus, U. S. Patent No. 2,927,351, March 8, 1960.

(41) T. W. Pierson, Screen, Projector, and Sign Arrangement for Outdoor Advertising, U. S. Patent No. 3,069,970, December 25, 1962.

(42) B. M. Bodde, Jr., Projection Screen, U. S. Patent No. 2,372,173, March 27, 1945.

(43) T. F. Smith, Drive-in Theatre with Individual Car Screens, U. S. Patent No. 2,734,420, February 14, 1956.

(44) J. J. Matelena, Inflatable Aerial Projection Display Device, U. S. Patent No. 2,592,444, April 8, 1952.

(45) D. McCulley, Means of Staging Productions, U. S. Patent No. 3,035,836, May 22, 1962.

(46) M. Hensoldt & Sohne, Optische Werke, AG., Optical Device for the Observation of a Focusing Screen such as a Ground-glass Plate, British Patent No. 909,431, October 31, 1962.

(47) R. Pabst et al, Plural Lens Optical Screen, U. S. Patent No. 2,915,935, December 8, 1959.

III. Preliminary Theoretical Investigation

Two preliminary investigations were made in addition to the scheduled literature search.

The first study was undertaken to determine if a major reformulation of the theory of resolution and/or its measurement would be required to adequately describe the resolution properties of rear projection screens. This study was important because resolution is the most important parameter of a projection screen material next to diffusion and also because conventional resolution theory was developed for image forming optical elements and not light scattering display screens.

The results of this study are directly applicable to the design of laboratory equipment to be used in measuring the resolution of Corning Glass Works materials for applications in rear projection screens.

The second study deals with the theoretical losses associated with the transmittance of light through uncoated hollow optical fibers made from Molybdenum impregnated Vicor brand glass. This supplemented work which was being done for us by our Danville, Virginia, facility.

A. Applicability of Modulation Transfer Function Theory to the Assessment of Rear Projection Screen Resolution

High resolution photographs contain large quantities of densely packed information. If this is to be viewed by projection the medium on which it is displayed must be capable of resolving the necessary level of detail. An information display system is made up of a combination of many individual elements typically a projector, transparencies containing data, some type of screen on which it is displayed, and the observer's optics. The observer's optics, i. e., his eyes, may be aided by additional magnifiers or measuring instruments. The resolution of a system as a whole will be influenced by each element which must be capable of meeting certain minimum resolution requirements.

Modulation transfer function (MTF) theory has been extensively used to evaluate the resolution of optical systems and components over the last few years. The MTF is a measure of how well the contrast of a particular size detail is transmitted through an optical system as a function of detail size. These functions, introduced in optics by Duffieux[1], extensively applied to television systems by Schade[2], and further developed theoretically by Linfoot[3], Hopkins[4,5], Sayanagi[6] and O'Neill[7], have completely replaced Rayleighs concept of two point resolution[8,9]. Further the close relation between optical and electrical systems from the point of communications theory has been shown[10,11]. This whole new approach has been discussed in a collection of papers edited by O'Neill[12] and in many other articles[13-19]. The most recent review was at a Symposium on <u>The Practical Application of Modulation Transfer Functions</u> at the Perkin Elmer Corporation in 1963[20-26]. These techniques have also been applied to photographic materials[27-36].

Application of the sampling theorem to optical image formation has led to the concept of information capacity of optical images[37-41] and of photographic films[42-45]. The information capacity is related to the MTF of the material and it characterizes the amount of information which can be retained, for example after display, on a projection screen.

With only a few exceptions these techniques have been applied to image forming devices such as lenses, curved mirrors, telescopes, microscopes, projectors, etc. Very little has been published concerning investigation of non-imaging components like transparent plates, flat mirrors, and of primary interest, light scattering display materials. The importance of this study can be seen by considering the unique differences between image forming devices for which the theory was developed and light scattering display materials to which it is to be applied. Lenses are designed to be used at one given diameter, object distance and magnification. They are usually uniformly illuminated and almost all of the light incident on them passes through forming an image in one particular plane.

Quite different constraints are encountered when using a projection screen. It can never be uniformly illuminated if it is to display information. A significant portion of the incident energy is backscattered toward the projector, some is scattered laterally through the screen, and that which passes through is unevenly distributed over an appreciable solid angle. In general the information displayed must be observed from many different directions, at varying distances from the screen, and possibly under additional magnification.

A mathematical development of the measure of resolution, its significance, and its relation to measurable quantities will first be given followed by a review of conventional techniques used to measure resolution, based on this theory. Their applicability to projection screens will be discussed after which the results of the study are summarized.

1. Theoretical Bais of Modulation Transfer Function Theory

To better understand the importance of the MTF, a mathematical representation of image formation is given. This will illustrate the convolution concept of image formation and introduce the associated concept of spatial frequency spectra of object and image intensity distributions and their important inter-relation. From this foundation the MTF will be defined and its critical importance seen. Although the developments will be restricted to one dimension for simplicity, all of the results are directly applicable to the two dimensional general case.

Consider the incoherent diffraction limited optical system shown in Figure 1.

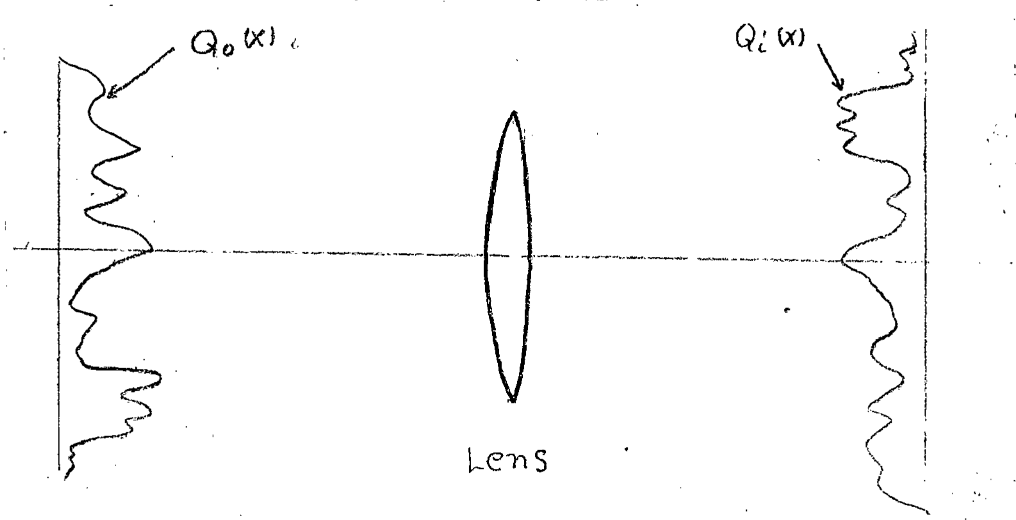


Figure 1. Diffraction Limited Image Forming System

Let o(x) and i(x) be one dimensional intensity distributions in the object and image planes respectively, and defined as

$$o(x) = Q_o(x') \; \delta \quad (x'-x) \qquad (1)$$

$$i(x) = Q_i(x') \quad S \quad (x'-x) \qquad (2)$$

where $Q_o(x)$ and $Q_i(x)$ are properly normalized weighting functions, with $\delta(x'-x)$ being the Dirac δ function and $S(x'-x)$ its image, the line spread function. The image of a general object can be found if the line spread function is known, since the image of a general one dimensional object can be made up from a sum of such line images.

Define the Fourier spectra of the object, its image, and the line spread function respectively as

$$O(R_x) = \int_{-\infty}^{\infty} o(x)\, e^{-i\, 2\pi x R_x}\, dx \qquad (3)$$

$$I(R_x) = \int_{-\infty}^{\infty} i(x)\, e^{-i\, 2\pi x R_x}\, dx \qquad (4)$$

$$\phi(R_x) = \int_{-\infty}^{\infty} S(x)\, e^{-i\, 2\pi x R_x}\, dx \qquad (5)$$

To determine the relations between these six quantities we begin by writing the convolution integral describing how the image is formed in terms of the object intensity distribution and the line spread function

$$i(x) = \int_{-\infty}^{\infty} o(x')\, S\, (x-x')\, dx' \qquad (6)$$

Substituting (6) into (4) gives

$$I(R_x) = \int_{-\infty}^{\infty} e^{-i\, 2\pi x R_x} \cdot \left[\int_{-\infty}^{\infty} o(x')\, S\, (x-x')\, dx' \right] dx \qquad (7)$$

The order of integration in (7) can be changed if o(x) and s(x) are square-integrable[46], i.e.,

$$\int_{-\infty}^{\infty} |o(x)|^2 \, dx < \infty \tag{8}$$

and

$$\int_{-\infty}^{\infty} |S(x)|^2 \, dx < \infty$$

which they are, hence (7) can be written as

$$I(R_x) = \int_{-\infty}^{\infty} o(x') \cdot \left[\int_{-\infty}^{\infty} e^{-i\,2\pi x R_x} S(x-x')\,dx\right] dx' \tag{9}$$

We know from the shifting theorem that

$$\int_{-\infty}^{\infty} e^{-i\,2\pi x R_x} S(x-x')\,dx = e^{-i\,2\pi x' R_x} \phi(R_x) \tag{10}$$

thus (9) becomes

$$I(R_x) = \phi(R_x) \int_{-\infty}^{\infty} o(x') e^{-i\,2\pi x' R_x} \, dx' \tag{11}$$

The integral is clearly just the Fourier transform of $o(x')$ and the final result is

$$I(R_x) = \phi(R_x) \cdot O(R_x)$$
$$\phi(R_x) = \frac{I(R_x)}{O(R_x)} \tag{12}$$

The function $\phi(R_x)$ is a weighting function controlling the transfer of power as a function of spatial frequency between an object and its image.

It in essence relates the contrast in the image to that in the object. For this reason it is sometimes called the contrast transfer function but more conventionally the MTF.

The contrast γ of a sinusoidal intensity distribution, Figure 2, is defined as

$$\gamma = \frac{I_{max} - I_{min}}{I_{max} + I_{min}} = \frac{(I_{max} - I_{min})/2}{(I_{max} + I_{min})/2} \qquad (13)$$

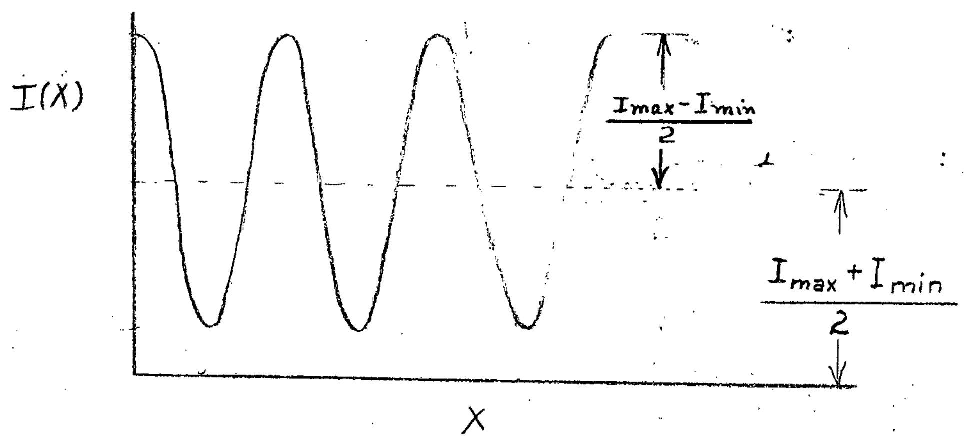


Figure 2. The Physical Meaning of Contrast

It is clear from (13) and Figure 2 this is just the ratio of the AC to DC power in the sinusoidal pattern.

Usually only the normalized transfer function $T(R_x, R_y)$ is used,

$$T(R_x) = \frac{\phi(R_x)}{\phi(0)} \qquad (14)$$

Thus $T(o) = 1$. Therefore the one dimensional MTF can be expressed as

$$T(R_x) = \frac{\gamma_i}{\gamma_o} \qquad (15)$$

where γ_i and γ_o are the contrasts in the sinusoidal object and image distributions. It should also be noted that γ_i and γ_o are independent of any absolute power and more importantly γ_i is independent of any uniform attenuation of intensity in the image forming process.

Other than sinusoidal patterns have been used[47-51]. However, to make the data meaningful it must be reduced to the equivalent sinusoidal response. Thus much time and work is saved by initially measuring the optical component using sine-wave techniques.

In keeping with the universally accepted nomenclature[52] the transfer function is a complex quantity called the optical transfer function. Its modulus is called the modulation transfer function. The phase transfer function describes the spatial phase across a sinusoidal pattern, and is determined by comparing the spatial location of the image and object distributions. The variable of the MTF is called spatial frequency and is given in units of cycles per millimeter or lines per millimeter (the latter only when no confusion can occur with television lines, as two television lines equal 1 cycle).

2. Experimental Techniques Based on MTF Theory

There are a great variety of techniques by which the MTF of an optical element can be obtained. Each has its own particular advantages and limitations. These techniques can be classified into three main areas.

a. Measurement of sinusoidal objects and images.

b. Spread function analysis.

c. Interferometric techniques.

The following inter-relations summarize the previous theoretical development

$$\begin{array}{ccccc} i(x) & = & S(x) & * & o(x) \\ \downarrow\uparrow & & \downarrow\uparrow & & \downarrow\uparrow \\ I(R_x) & = & T(R_x) & \cdot & O(R_x) \end{array} \qquad (16)$$

where * and $\rightleftharpoons$ denote convolution and Fourier transformation respectively.

a. Direct Measurement of Sinusoidal Objects and Images

The most straightforward way to measure $T(R_x)$ is to use as an object a transparency whose transmittance varies as the spatial coordinate x^{53}. The spectrum of the object $O(R_x)$ is the pair of delta functions, $\delta(R_x) + \delta(-R_x)$ plus a d.c. term.

The product of $O(R_x)$ with $T(R_x)$ modifies the ratio of AC to DC power simply by relatively decreasing the power in the AC term. The image $i(x)$ is also sinusoidal but of somewhat lower contrast because of $T(R_x)$. The image can be directly recorded on film and the contrasts obtained by densitometry. The MTF is computed according to (15) by taking the ratio of the contrast in the image to the contrast in the object. By using several different spatial frequencies, the MTF properties of the component under test can be determined.

To measure the MTF of a rear projection screen the primary image must be projected onto it. This could either be re-imaged onto a photographic plate by means of a second lens or scanned either at the screen or after projection onto a scanner. Scanning has the advantage of being strictly linear and also not requiring liquid chemical development as do photographic films. It can be done very fast and further it makes the data available for additional electronic processing. Here the contrast in the image without the screen is taken as the reference rather than the contrast of the object. This then compensates for the MTF of all the optical components except the screen which is to be measured.

At the lower spatial frequencies the projected image averages over many of the scattering irregularities of the screen and the MTF obtained is a very good measure for those frequencies. At higher spatial frequencies near the characteristic size of the irregularities in the screen, the lines in test object become distorted and bent and the resulting MTF becomes dependent on the average amount of this distortion. The MTF can be expected to fall sharply near this characteristic spatial frequency. However, these are exactly the conditions under which information will be displayed and therefore the measured MTF will continue to be a valid measure of the screens resolution.

If a spatial frequency pattern of frequency R_x is projected onto a screen and observed at an angle θ, measured with respect to the screen normal, it will appear to be of frequency R_x' given by,

$$R_x' = R_x / \cos \theta \tag{17}$$

To properly use the MTF curve of a screen for off axis viewing, the values of R_x should be appropriately modified by the factor $\cos \theta$. This simply means the contrast of a given spatial frequency is independent of the angle at which it is viewed. This may be true of the screen alone but not necessarily of a whole system. This is because the optics which view the screen will be imaging R_x' rather than R_x hence their MTF at R_x' rather than at R_x must be considered.

Methods commonly used to produce variable-transmission sinusoidal patterns for this type of measurement involve the generation of an image and its recording on a photo-sensitive material; in such procedures, the intensity variation in the image is proportional to the desired transmission variation in the photorecording. These in general cannot be purchased but must be made by each group.

A variety of procedures and apparatus have been employed to generate such sinusoidal test patterns. Schade[54] utilized sound recording techniques. Kapany and Pike[55], Julich[56] and others[57] used devices to scan Ronchi rulings and other periodic objects. Shaw[44] used a slit whose intensity was modulated sinusoidally in time. Interferometry has been utilized by several authors[58-62] to produce fringes suitable as image evaluation test patterns. Variable-area sine-wave patterns have been converted optically to variable-intensity images by Selwyn[63] and Lamberts[64,65] using cylindrical optics and by Desprez and Pollet[66] with a lens, the pupil of which, was a narrow slit.

The photorecording of an optical image which varies sinusoidally in intensity is not only difficult but imposes certain limitations. The use of nonlinearly responding materials such as silver halide films require additional care in preparing the test objects if they are to be free of harmonic distortion. Compensating techniques using suitable combinations of positive and negative materials have been used by Kelley et al[67], and others[68,69]. Scott[70] suggests a way to produce such objects whereby nonlinearities can be compensated for by appropriately modifying an area pattern used in their production.

b. Spread Function Analyses

The MTF of a rear projection screen can be measured by projecting a line image onto it, and Fourier transforming the intensity distribution of the line spread function s(x)[71-73] formed by a lens some distance behind it where,

$$s(x) = U(x) \cdot U^{*}(x) \qquad (18)$$

and U(x) is the amplitude distribution in the line spread function. The superscript* denotes the complex conjugate. Rather than measure s(x) and Fourier transform, the line image may be projected onto a scanner whose transmittance varies sinusoidally with the spatial coordinate x. This represents a convolution of s(x) with cos $2\pi(x R_x + \omega t)$; refer to equation (16) and also the previous discussion on using sinusoidal test objects. Because of the motion of s(x) across the scanner in time its output will be a sinusoidal signal whose contrast is a measure of $T(R_x)$.

Two commercial instruments based on this concept have recently been developed[74,75]. The lens under test forms an image, of a line source into a rotating sinusoidal mask. The MTF is obtained by electronically extracting the AC signal. Changes in spatial frequency are produced by using a rotating one dimensional Fresnel pattern.

An identical but much less sophisticated instrument has been described by Hacking[76]. Here a microscope objective relays the image of a line source, formed by the lens under test to a slit immediately ahead of a sinusoidal test chart. Data required to compute the MTF is obtained by translating the pattern to two different positions and measuring the transmitted intensity. The pattern behind the slit is rotated to change its effective spatial frequency.

A conceptually identical device is also described by Herriott[77], where a variable-area pattern is used as the object and its image is scanned across a slit by means of rotating drum on which the pattern is mounted. The spatial frequency of the pattern changes around the drum hence it scans through a range of frequencies each cycle of rotation. A phototube behind the slit detects changes in intensity and the MTF is computed electronically. A more elaborate device measuring both the MTF and the phase transfer function is outlined by Shannon and Neuman[78]. Many other authors have contributed to this literature[79.80].

The limitations of these techniques center around the formation of a line source on the screen and secondly on the screens scattering properties and the angular size of the second lens as seen from the screen. The surface on which the line source is formed may contain micro irregularities. If the line is considerably wider than this micro structure a good average will be obtained and the scattered intensity will be independent of where on the screen the line image is located. If, however, the line image is of the same dimensions as the irregularities, it will be significantly distorted in both shape and position which will change $s(x)$ and hence $T(R_x)$.

Specifically $T(R_x)$ again becomes a measure of the average distortion and influences only the high frequency characteristics. However, if the line image is not a good average over the irregularities the MTF can be changed by slightly displacing the screen, i. e., the sample taken by the line image is too small.

The same is true if instead the scattering takes place in a volume rather than on a surface and volume irregularities are considered.

Differences in the measured MTF should not be expected between the two different techniques described even at spatial frequencies near those of the irregularities unless the slit image is too small to properly sample the scatters. It will be the best possible estimate when using a sinusoidal pattern because of better averaging, and may vary erratically when a point or line source is used depending on the relative size of the line image and the size of the irregularities.

A distinction must be drawn between the inherent and measured MTF of the screen. An estimate of the inherent MTF can be found by Fourier transforming the intensity distribution of a line source projected onto it, but the measured MTF may or may not be a good estimate depending on how carefully all detail is considered. The MTF measured directly on the screen will always be greater than or equal to that measured by using an additional lens. However using the second lens can be a good approximation to the lens in the observer's eye. The relative influence of these factors on the measured MTF can only be decided by considering all of the necessary parameters of a given projection and viewing system.

When a second lens is used to transfer the image from the screen to a photographic plate or scanner it's MTF must also be considered. Because of the highly nonuniform scattering properties of rear projection screens the MTF of the transfer lens $T'(R_x)$ will depend upon the illumination across it, termed the aperture illumination function $E(x)$. This is the product of the intensity distribution $B(x)$ from the source withe the aperture transmission function $C(x)$,

$$E(x) = B(x) \cdot C(x) \qquad (19)$$

The function $E(x)$ is effectively an apodigation[81-83] of the aperture which may change the MTF of the lens. This apodization essentially is a spatial frequency filter which operates on the information in the aperture plane rather than in the Fraunhofer plane.

From the diffraction theory of image formation[1,84-87] the MTF of the transfer lens can be written

$$T'(R_x) = \int_{-\infty}^{\infty} \sqrt{E(\beta)} \cdot \sqrt{E(\beta - R_x)}\, d\xi \qquad (20)$$

where β is a transformed coordinate across the aperture. The convolution must be in terms of amplitude and not intensities thus the square root of $E(\beta)$. This can only be done because the aperture function is real.

Figure 3 shows the angular scattering function of a screen and the aperture distribution for two different viewing angles.

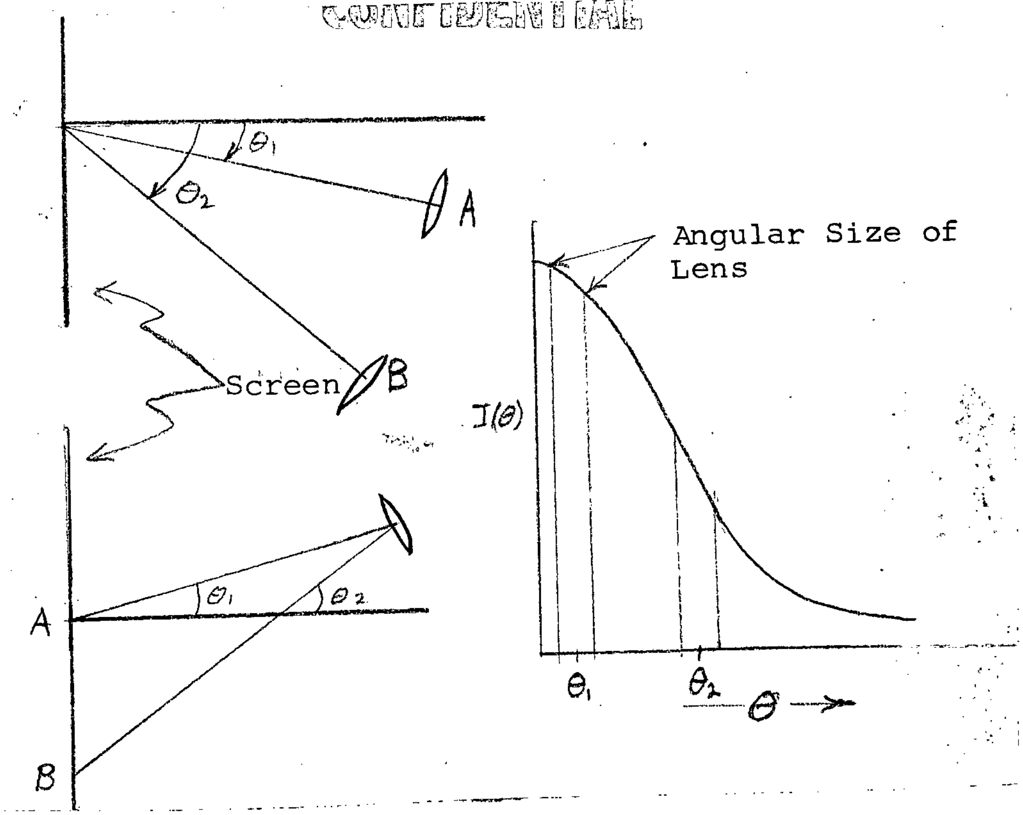


Figure 3. Angular Scattering Distribution of a Screen and the Associated Aperture Distributions for Two Viewing Angles

In this example lens A is more uniformly illuminated than B. It should be noted the difference in absolute intensity between lenses A and B will not influence $T'(R_x)$. This approach is also equivalent to looking at two different points located at different places on the screen, thus $T'(R_x)$ will also change with the location of the detail. Figure 4 illustrates the effect of moving a lens from A back to B which changes its angular size and hence $E(\beta)$ which is equivalent to using a smaller lens at A, both of which tend to make $E(\beta)$ more uniform.

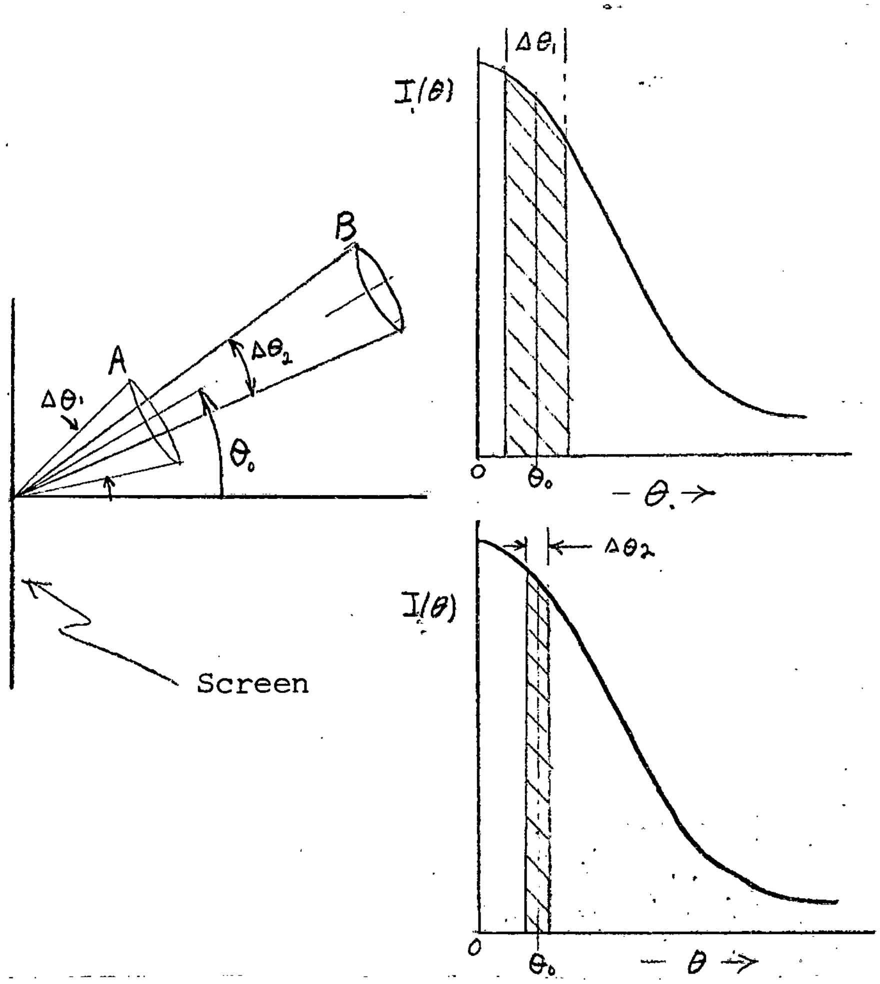


Figure 4

An important topic for further investigation is the influence of screen thickness and scattering characteristics on MTF. Intuitively the thicker the screen and the greater the scattering in it, the lower will be the resolution. A complete understanding of this relationship is therefore important in the design of high resolution screens. It may be that resolution higher than a given limit can only be achieved by surface scattering rather than volume scattering. At this point the size of the surface scatters will also become important. The results of such a study in relation to resolution requirements will obviously have a direct influence on any materials program.

c. Interferometric Techniques

A different class of techniques assumes a uniform aperture amplitude distribution thus requiring only a measurement of the phase variations of the wavefront over the aperture[89]. These measurements can be made by using a modified Michelson or Tyman-Green Interferometer[88]. Another similar technique suggested by Hopkins[2] and first realized by Baker[90] is based upon measuring the light flux in the interference pattern formed by recombination of two sheered wavefronts.

All of these methods impose the constraint of requiring the object under test to preserve the spatial coherence of the incident wavefront. This is not compatable with any type of light scattering projection screen and therefore these and other related techniques will not be considered any further here.

3. Conclusion

After presenting the mathematical foundations of modulation transfer function theory and considering conventional techniques compatable for measuring the MTF of rear projection screens, there seems to be no justification for thinking any extention of present theory is required. Certain conventional techniques are not applicable to measuring projection screens because the spatial coherence of the wavefront is not preserved. However, very many techniques are still valid if the physical characteristics of the screen are properly considered. Of these the relative size of the projected detail to the size of the irregularities producing the scattering is the most important. Some techniques are highly sensitive to this while others are not.

Scanning and additional electronic processing can yield directly the resolution characteristics of a screen or complete display system.

The influence of nonuniform illumination across the observing optics was investigated. The specific influence depends upon the scattered intensity distribution and also very much on the specific details of the viewing system and must be considered individually for each system.

This study has shown the applicability of conventional resolution theory to light scattering display media and also has uncovered many interesting topics to be given further study in the theoretical and experimental phases of our program of investigating Corning materials.

References

(1) P. M. Diffieux, "L'integrale de Fourier et ses Applications a l'Optique," (Rennes, 1946).

(2) O. H. Schade, "Method of Measuring Optical Sine-Wave Spatial Spectrum of Television Image Display Devices," SMPTE, 67, 561 (1958).

(3) E. H. Linfoot, Fourier Methods in Optical Image Evaluation, (The Focal Press, London, 1960).

(4) H. H. Hopkins, "The Frequency Response of a Defocused Optical System," Proc. Roy. Soc., A231, 91 (1955).

(5) H. H. Hopkins, "The Application of Frequency Response Techniques in Optics," Proc. Phys. Soc., 79, 889 (1962).

(6) K. Sayanagi, Proceedings of the Conference on Optical Instruments and Techniques, (John Wiley, New York, 1963).

(7) E. L. O'Neill, Introduction to Statistical Optics, (Addison-Wesley Publishing Co., Reading, 1963).

(8) F. A. Jenkins and H. E. White, Fundamentals of Optics, (McGraw-Hill, New York, 1950).

(9) A. Sommerfeld, Optics, (Academic Press, New York, 1964).

(10) P. Elias, D. S. Grey, D. Z. Robinson,"Fourier Treatment of Optical Processes," J. Opt. Soc. Am., 42, 127 (1952).

(11) P. Elias, "Optics and Communication Theory," J. Opt. Soc. Am., 43, 229 (1953).

(12) E. L. O'Neill, "Communication and Information Theory Aspects of Modern Optics," (1962).

(13) E. Ingelstam, E. Djurle, And B. Sjogren, "Contrast-Transmission Functions Determined Experimentally for Asymmetrical Images and for the Combination of Lens and Photographic Emulsions," J. Opt. Soc. Am., 46, 707 (1956).

(14) B. R. Frieden,"Polynomial Expansion in Classical Aberrations and Spatial Frequency for the Wave-Aberrated Optical Transfer Function of an Axially Asymmetric Lens System," Optica Acta, 11, 33 (1964).

(15) R. Barakat, "Computation of the Transfer Function of an Optical System from the Design Data for Rotationally Symmetric Aberrations, Part I. Theory," J. Opt. Soc. Am., 52, 985 (1962).

(16) R. Barakat and M. V. Morello, "Computation of the Transfer Function of an Optical System from the Design Data for Rotationally Symmetric Aberrations. Part II. Programming and Numerical Results," J. Opt. Soc. Am., 52, 992 (1962).

(17) R. Barakat and D. Levi, "Transfer Functions and Total Illuminance of High Numerical Aperture Systems Obeying the Sine Condition," J. Opt. Soc. Am., 53, 324 (1963).

(18) H. Kubota and T. Asakura, "Optics in Japan: With Special Reference to the Study of Transfer Function and Its Application in Optical Industries," Applied Optics, 1, 284 (1963).

(19) F. D. Smith, "Optical Image Evaluation and the Transfer Function," Applied Optics, 2, 335 (1963).

(20) R. M. Scott, "Introduction," Phot. Sci. & Eng., 9, 237 (1963).

(21) A. Offner, "Optical Design and Modulation Transfer Functions," Phot. Sci. & Eng., 9, 240 (1963).

(22) R. E. Hufnagel, "Random Wavefront Effects," Phot. Sci. & Eng., 9, 244 (1963).

(23) F. Scott, "Film Modulation Transfer Functions," Phot. Sci. & Eng., 9, 248 (1963).

(24) M. D. Rosenau, Jr., "Image-Motion Modulation Transfer Functions," Phot. Sci. & Eng., 9, 252 (1963).

(25) K. Preston, Jr., "Modulation Transfer-Function Instrumentation," Phot. Sci. & Eng., 9, 256 (1963).

(26) R. M. Scott, "Summary and Example," Phot. Sci. & Eng., 9, 261 (1963).

(27) F. H. Perrin, "On the Point and Line Spread Functions of Photographic Images," J. Opt. Soc. Am., 48, 934 (1958).

(28) R. L. Lamberts, "Measurement of Sine-Wave Response of a Photographic Emulsion," J. Opt. Soc. Am., 49, 425 (1959).

(29) F. H. Perrin, "Methods of Appraising Photographic Systems," J. SMPTE, 69, 151, 239 (1960).

(30) D. H. Kelly, "Systems Analysis of the Photographic Process, Part I," J. Opt. Soc. Am., 50, 269 (1960).

(31) D. H. Kelly, "Systems Analysis of the Photographic Process, Part II. Transfer Function Measurements," J. Opt. Soc. Am., 51, 319 (1961).

(32) J. A. Eyer, "Spatial Frequency Response of Certain Photographic Emulsions," J. Opt. Soc. Am., 48, 938 (1958).

(33) J. H. Altman and H. J. Zweig, "Effect of Spread Function on the Storage of Information on Photographic Emulsions," Phot. Sci. & Eng., 7, 173 (1963).

(34) J. L. Simonds, J. R. Kelch, and G. C. Higgins, "Analysis of Fine-Detail Reproduction in Photographic Systems," Applied Optics, 3, 23 (1964).

(35) H. Thirty, "The Contrast Transmission of a Sinusoidal Signal of Large Amplitude by Photographic Materials," J. Phot. Sci., 10, 352 (1962).

(36) Eastman Kodak Co., "Modulation Transfer Data for Kodak Films," 2 ed., Pamphlet No. P-49.

(37) G. Toraldo di Francia, "Resolving Power and Information", J. Opt. Soc. Am., 45, 497 (1955).

(38) H. Gamo, J. Appl. Phys., Japan 25, 431 (1956); 26, 102 (1957); 26, 414 (1957); 27, 577 (1958).

(39) D. Gabor, "Light and Information," Progr. Opt., 1, 109 (1961).

(40) R. Barakat, "Application of the Sampling Theorem to Optical Diffraction Theory," J. Opt. Soc. Am., 54, 920 (1964).

(41) R. C. Jones, "Information Capacity of Radiation Detectors and of Light," Applied Optics, 2, 351 (1963).

(42) H. J. Zweig, G. C. Higgins, and D. L. MacAdam, "On the Information-Detecting Capacity of Photographic Emulsions," J. Opt. Soc. Am., 48, 926 (1958).

(43) R. C. Jones, "Information Capacity of Photographic Films," J. Opt. Soc. Am., 51, 1159 (1961).

(44) R. Shaw, "The Application of Fourier Techniques and Information Theory to the Assessment of Photographic Image Quality," Phot. Sci. & Eng., 6, 281 (1962).

(45) C. S. McCamy, "On the Information in a Microphotograph," Applied Optics, 4, 405 (1965).

(46) A. Papoulis, The Fourier Integral and its Applications, (McGraw-Hill Book Co., New York, 1962).

(47) F. E. Washer and F. W. Roseberry, "New Resolving Power Test Chart," J. Opt. Soc. Am., 41, 597 (1951).

(48) R. N. Hotchkiss, F. E. Washer and F. W. Roseberry, "Spurious Resolution of Photographic Lenses," J. Opt. Soc. Am., 41, 600 (1951).

(49) A. G. Tull and C. J. Bell, "Grid Images Applied to the Assessment of Definition," J. Phot. Sci., 11, 78 (1963).

(50) P. Hariharan, "Resolution of an Annulus Test Object," J. Opt. Soc. Am., 45, 44 (1955).

(51) K. P. Miyake, "Effect of Using Siemens Star as Scanning Chart in Measurement of Response Function," Science of Light, 7, 9 (1958).

(52) E. Ingelstam, "Nomenclature for Fourier Transforms of Spread Functions," Applied Optics, 3, 96 (1964).

(53) J. D. Armitage, A. W. Lohmann, and R. B. Herrick, "Absolute Contrast Enhancement," Applied Optics, 4, 445 (1965).

(54) O. H. Schade, "Image Gradation, Graininess and Sharpness in Television and Motion Picture Systems. II: The Grain Structure of Motion Picture Images--An Analysis of Deviations and Fluctuations of the Sample Number," J. SMPTE, 58, 181 (1952).

(55) N. S. Kapany and J. N. Pike, "Scanning Integrator for Producing Sinusoidal Test Objects," J. Opt. Soc. Am., 46, 867 (1956).

(56) H. Julich, "Generation of Sinusoidal Light Intensity," Applied Optics, 2, 263 (1963).

(57) N. S. Kapany and J. N. Pike, J. Opt. Soc. Am., 46, 867, (1956).

(58) J. S. Wilczynski, "Some Properties of Photographic Image Recording," Proc. Phys. Soc. (London), 77, 17 (1961).

(59) M. V. R. K. Murty, "An Interferometric Method for Producing Variable-Frequency Sine-Wave Pattern," J. Opt. Soc. Am., 50, 1084 (1960).

(60) E. Inglestam, "Michtlineare Udertragungsglieder fur Optische und Photograthische Abbildung-Einige Ansautze zur Exterimentellen and Theoretischen Behandlung," Optik, 18, 593 (1961).

(61) F. Grum, "Modification and Use of a Michelson Interferometer to Produce Variable-Frequency Sinusoidal Patterns," Phot. Sci & Eng., 7, 96 (1963).

(62) W. H. Steel, "A Polarization Interferometer for the Measurement of Transfer Functions," Optica Acta, 11, 9 (1964).

(63) E. W. H. Selwyn, Phot. J., 88B, 46 (1948).

(64) R. L. Lamberts, "Application of Sine-Wave Techniques to Image-Forming Systems," J. SMPTE, 71, 635 (1962).

(65) R. L. Lamberts, "The Production and Use of Variable-Transmittance Sinusoidal Test Objects," Applied Optics, 2, 273 (1963).

(66) R. Desprez and J. Pollet, "Production and Use of a Sine-Wave Test-Object," J. Phot. Sci., 12, 202 (1964).

(67) D. H. Kelley, M. E. Lynch, and D. S. Ross,"Improved Sinusoidal Test Charts," J. Opt. Soc., Am., 48, 858, (1958).

(68) M. E. Rabedeau and A. D. Bates, "Harmonic Distortion in Variable-Transmittance Sinusoidal Test Objects," Phot. Sci. & Eng., 8, 149 (1964).

(69) J. L. Simonds, J. R. Kelch, and G. C. Higgins, "Analysis of Fine-Detail Reproduction in Photographic Systems," Applied Optics, 3, 23 (1964).

(70) F. Scott, "The Production of Variable-Transmission Sinusoidal Patterns and Other Images," Phot. Sci. & Eng., 9, 86 (1965).

(71) K. Birch, "A Scanning Instrument for the Measurement of Optical Frequency Response," Proc. Phys. Soc., 77, 901 (1961).

(72) R. Barakat and M. V. Morello, "Computation of the Transfer Function of an Optical System from the Design Data for Rotationally Symmetric Aberrations. Part II. Programming and Numerical Results," J. Opt. Soc. Am., 52, 992 (1962).

(73) R. Barakat, "Numerical Results Concerning the Transfer Functions and Total Illuminance for Optimum Balanced Fifth-Order Spherical Aberration,"J. Opt. Soc. Am., 54, 38 (1964).

(74) Optics Technology, Inc., "Modulation Transfer Function Analyzers K-1 and K-1a".

(75) R. & J. Beck Limited, "Equipment for Measuring the Response of Optical Systems", Ad.

(76) K. Hacking, "An Optical Method of Obtaining the Frequency Response of a Lens," Nature, 181, 1158 (1958).

(77) D. R. Herriott, "Recording Electronic Lens Bench," J. Opt. Soc. Am., 48, 968 (1958).

(78) R. R. Shannon and A. H. Newman, "An Instrument for Measurement of the Optical Transfer Function,"Applied Optics, 2, 365 (1963).

(79) P. Lindberg, "Measurement of Contrast Transmission Characteristics in Optical Image Formation," Optica Acta, 1, 80 (1954).

(80) D. Kelsall, "Optical Frequency Response Characteristics in the Presence of Spherical Aberration Measured by an Automatically Recording Interferometric Instrument," Proc. Phys. Soc., 73, 465 (1959).

(81) E. L. O'Neill, "Transfer Function for an Annular Aperture," J. Opt. Soc. Am., 46, 285 (1956).

(82) I. O. Tannhauser, "Investigation of the Influence of Apodization on the Sine Wave Response of Photographic Lenses," Applied Optics, 4, 731 (1965).

(83) N. A. Finkelstein and C. H. Brumley, "Analog Fourier Transformer for Apodization Studies," J. Opt. Soc. Am., 49, 410 (1959).

(84) M. Born and E. Wolf, Principles of Optics, (The MacMillan Company, New York, 1964).

(85) A. Maréchal, Editions de la Revve d'Optique, Paris (1960).

(86) M. Françon, Modern Applications of Physical Optics, (Interscience Publishers, New York, 1963).

(87) G. B. Parrent, Jr., J. Opt. Soc. Am., 51, 143 (1961).

(88) S. Tolansky, An Introduction to Interferometry, (John Wiley & Sons, New York, 1955).

(89) R. Barakat and R. F. Van Ligten,"Determination of the Transfer Function of an Optical System from Experimental Measurements of the Wavefront,"Applied Optics, 4, 749 (1965).

(90) L. R. Baker, "An Interferometer for Measuring the Spatial Frequency Response of a Lens System,"Proc. Phys. Soc., (London) B68, 871 (1955).

B. Losses in Uncoated Hollow Glass Fibers

Since we are planning to investigate fiber optics materials for application in rear projection screens a theoretical study was made to determine the transmission losses through hollow uncoated opaque glass fibers.

The loss of power through such a fiber is due primarily to penetration of energy through the inner fiber wall. This is either absorbed if the fiber is not clear or else it is simply refracted out of the fiber and into the surrounding media.

The power penetrating the walls of the fiber as a function of incident angle θ and refractive index n of the wall relative to the hollow core, for two orthogonal polarizations is given by the familiar Fresnel equations.

$$\text{parallel} \quad \tau_P(\theta) = \mathrm{Tan}^2(\theta-\phi)/\mathrm{Tan}^2(\theta+\phi) \qquad (1)$$

$$\text{normal} \quad \tau_N(\theta) = \mathrm{Sin}^2(\theta-\phi)/\mathrm{Sin}^2(\theta+\phi) \qquad (2)$$

where $\tau_P(\theta)$, $\tau_N(\theta)$ are the transmission coefficients for the electric vector parallel and normal to the plane of incidence respectively, and ϕ is the angle of refraction given by Snell's law,

$$\phi = \mathrm{Sin}^{-1}\left(\frac{\mathrm{Sin}\,\theta}{N}\right) \qquad (3)$$

The reflection coefficients $R_P(\theta)$ and $R_N(\theta)$ are simply

$$R_P(\theta) = 1 - \tau_P(\theta) \qquad (4)$$

$$R_N(\theta) = 1 - \tau_N(\theta) \qquad (5)$$

For the Molybdenum impregnated glass all energy which passes through the first wall is absorbed hence $R_P(\theta)$ and $R_N(\theta)$ are valid reflection coefficients and describe the losses per reflection. For a clear non-absorbing glass fiber only a few percent of the energy incident at a point on the wall will be returned to the hollow core by reflection from the second wall if it is uncoated. Because total internal reflection is no longer responsible for the propagation of light down the fiber the numerical aperture must be given in terms of the angle at which the transmission coefficient $T(\theta,r)$ falls below some predetermined value.

It should be mentioned that a black glass is not necessarily more reflective than one which is clear. The contrast of the image in the black glass is much higher and subjectively influences the observer's evaluation of the reflected image seen. However absorbing glasses prevent cross-talk between fibers when used in a matrix.

The total loss of power at a given angle of incidence is determined by the length of the fiber, i. e., the number of reflection and the reflectivity. The number of reflections in a fiber of length L_O and diameter d, $r = L_O/d$, as a function of $\theta' = 90-\theta$ is found from the geometry of Figure 1 to be,

$$k(\theta,r) = r \operatorname{Tan} \theta' \qquad (6)$$

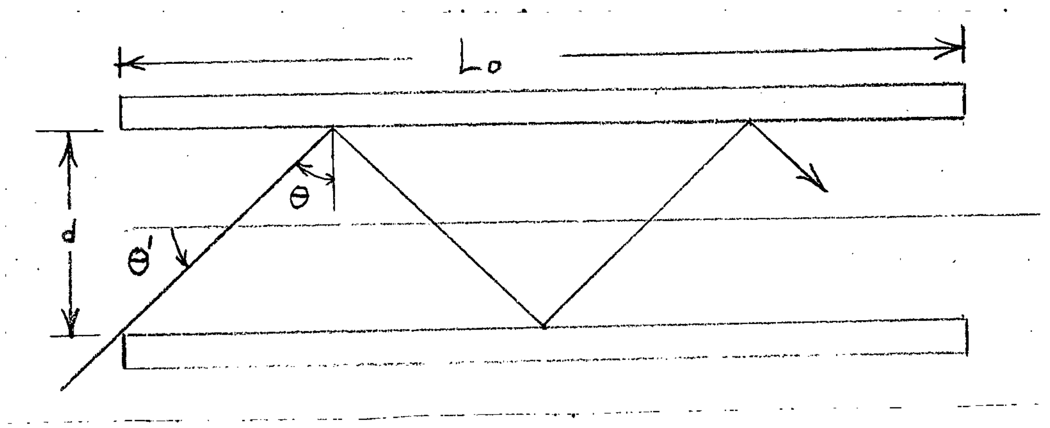


Figure 1. Geometry of Light Propagating Through a Hollow Reflective Fiber

Therefore the total transmission coefficient $T(\theta, r)$ for the fiber becomes,

$$T_P(\theta, r) = R_P(\theta)^{k(\theta, r)} \tag{7}$$

$$T_N(\theta, r) = R_N(\theta)^{k(\theta, r)} \tag{8}$$

expanding (7) and (8)

$$T_P(\theta, r) = \left[1 - \frac{\mathrm{Tan}^2\ (\theta - \phi)}{\mathrm{Tan}^2\ (\theta + \phi)}\right]^{r\ \mathrm{Tan}\ \theta} \tag{9}$$

$$T_N(\theta, r) = \left[1 - \frac{\mathrm{Sin}^2\ (\theta - \phi)}{\mathrm{Sin}^2\ (\theta + \phi)}\right]^{r\ \mathrm{Tan}\ \theta} \tag{10}$$

It is clear from (9) and (10) the losses are compounded as θ' increases. This is because both the reflection coefficient decreases and the number of reflections increases with increasing θ'.

One measure of the transmission properties through such fibers is the number of reflection, k, required to reduce the transmission coefficient to some given value. As an example, Figure 2 gives k as a function of the angle θ to reduce the transmission coefficient to .01. It is clear, even at large angles that only a very few reflections are required. It should be noted in using Figure 2, k must be integer. An equivalent measure is the ratio L_o/d, for which the transmission coefficient drops to .01 and is shown in Figure 3. Consider what these means in terms of fiber diameter, length, and angle of incidence.

The maximum length of a fiber with a diameter of 50 microns at $\theta = 75^o$; is .9 mm for the parallel component which undergoes 5 reflections and .4 mm for the normal component which reflects twice. It should be remembered each polarization is being considered independently. In view of the data given in Figures 2 and 3 and this example, it seems impractical to consider uncoated hollow fibers as a component for rear projection screens because of their high losses.

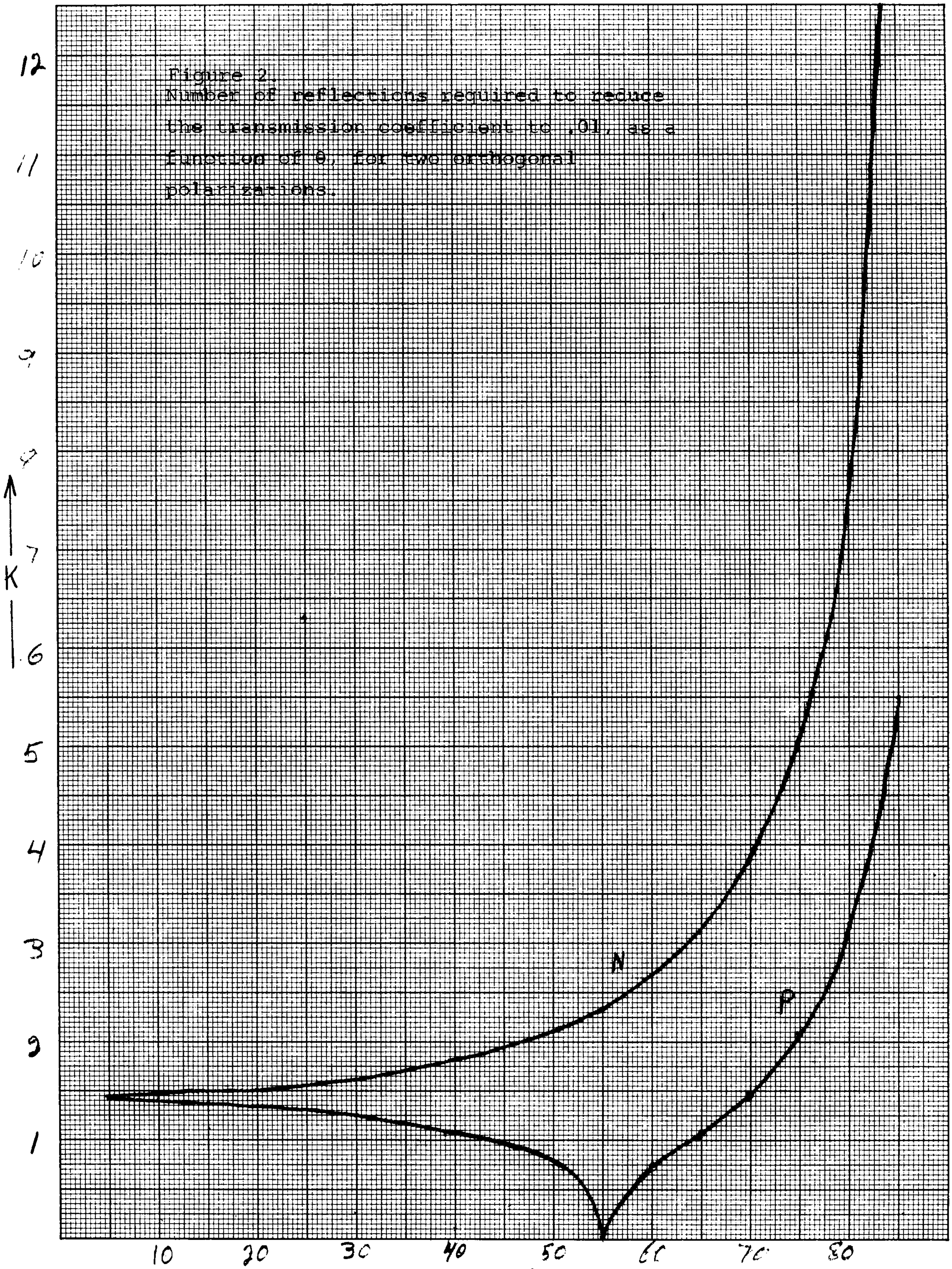


Figure 2.
Number of reflections required to reduce the transmission coefficient to .01, as a function of θ, for two orthogonal polarizations.

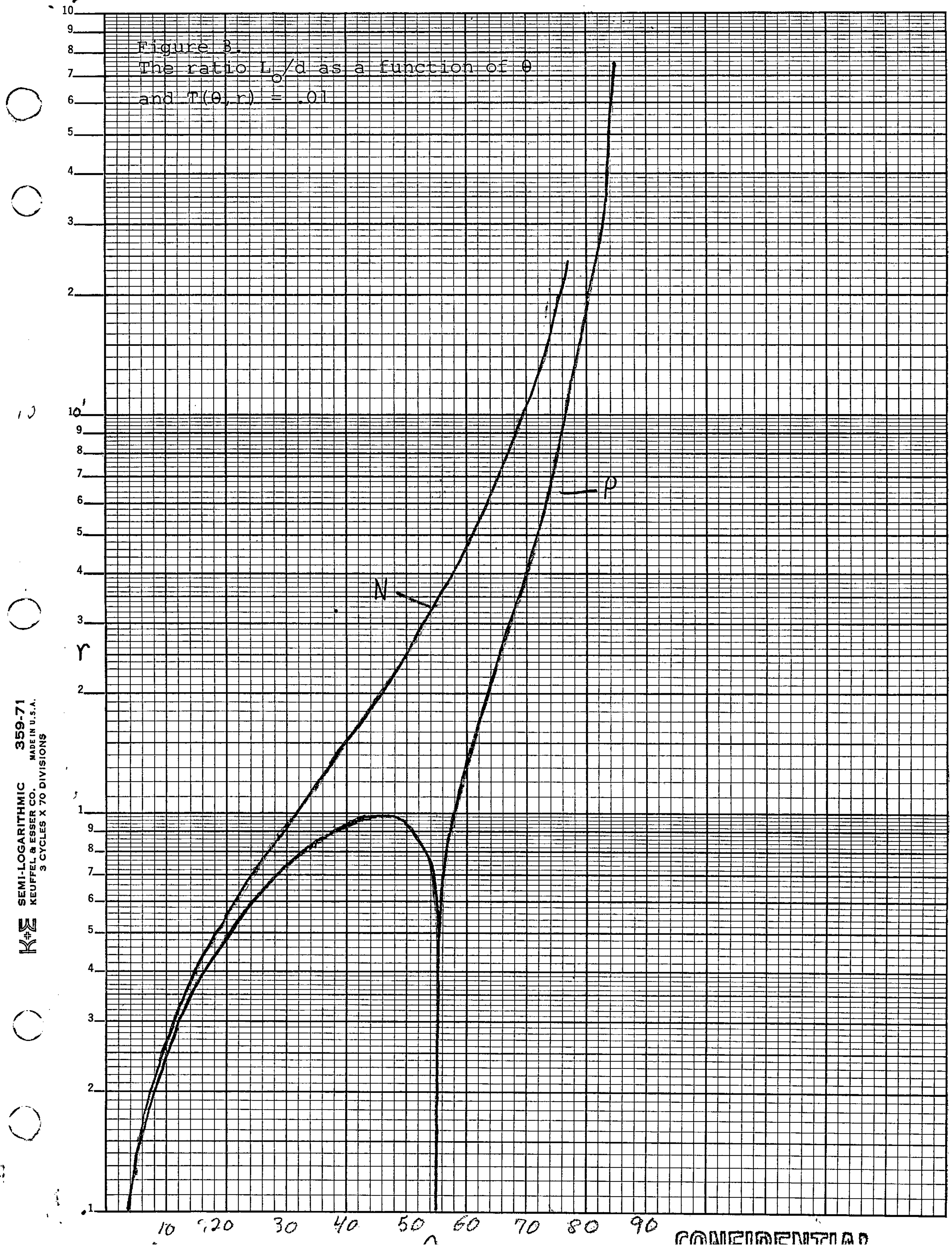


Figure 3.
The ratio L_o/d as a function of θ
and T(θ,r) = .01
N
P
r
10
20
30
40
50
60
70
80
90
SEMI-LOGARITHMIC 359-71
KEUFFEL & ESSER CO. MADE IN U.S.A.
3 CYCLES X 70 DIVISIONS

IV. Preliminary Investigations of CGW Materials

Since the main purpose of this contract is to study the applicability of Corning Glass Works' materials for improved screens for rear projection, we have started preliminary materials investigations. This is to increase our familiarity with CGW materials and their countless modifications.

It is also a part of this preliminary investigation to screen out materials which look promising and to start a more complete materials study of these. Although this has just started there are a wide variety of different materials which have already been singled out for further testing. Naturally specific requirements to the materials' groups must await a theoretical analysis of each different kind of material. However by starting this part of the effort early we have the advantage of guiding the theoretical work along definite avenues and toward specific material properties. This makes both the theoretical and experimental work more meaningful and directly applicable.

A. CGW Materials to be Studied in More Detail.

A trip to our facilities at Corning, New York, was made near the end of this phase of our work. Many technologies and materials applicable to the manufacture of rear projection screens were seen and discussed with various research personnel from a number of different departments.

Although there are more than five different Corning materials to be investigated the following discussions will be restricted to those which have been studied so far. The five major classes of materials to be investigated in detail are:

1. Glass Ceramics

Glass ceramics are materials that have been converted into crystalline ceramics from their original glassy state by the use of nucleating agents and heat treatment. A glass batch containing a suitable nucleating agent is melted and formed into a transparent glass by conventional glassmaking techniques. It is then cooled to temperatures inducing precipitation of the nucleating agents. Then, the nucleated material is heated to a temperature range in which growth of the nucleated crystals takes place and where typical crystal size is .1 to .3 microns. Composition of the material and degree of heat treatment determinethe type of crystallization and final properties such as its translucency and scattering properties. Three different samples of this material have been obtained.

2. Photosensitive Glasses

Photosensitive glass when exposed to ultra-violet light and heat behaves much like a photographic film or paper. An image is formed that is a permanent part of the glass and extends in depth throughout the body of the glass. Exposed areas turn an opalescent white after development by a heat treatment. The unexposed areas remain clear. Thus, any pattern can be reproduced in this glass by exposing and developing it. Screens containing over 350,000 precisely-located holes per square inch are produced by this technique. This material is known by the trademark "Fotoform". The Fotoform glasses can be converted by further heat treatment into a crystalline ceramic material. In this state the material can be translucent or opaque depending on how it is treated and it is mechanically harder and stronger than it was in the glassy state. It is marketed under the trademark "Fotoceram".

3. Multiform Glasses

These are formed by powdering a glass, pressing or slip casting the particles to shape and then firing at a high temperature. The particles are consolidated or sintered by fusion into a vacuum-tight structure.

Multiform products display properties similar to those of the parent glass. By controlling the size of the glass particles, the firing temperature and the firing time, multiform glasses can be made to have a wide variety of light scattering characteristics. The normal particle size is 5 microns but can be made as small as 3 microns with no large size limit and also can be made with a given distribution of particle sizes.

4. Porous Glasses

These glasses are composed of two different glasses with one being very much more soluable than the other. After the glass has been formed it is placed in a solution which leaches out the soluable glass leaving a very porous skeleton. The size of pores range from 10 Angstroms to 500 Angstroms. This gives the material a milky look but they eventually discolor because of the collection of organic substance in the pores. This can be avoided by covering the surfaces with a resin or similiar sealing material. The porous glasses can be made more translucent by filling the pores with an opalizing agent, the concentration of which can be varied to change the translucent properties to suit a particular application. We have one sample of this material and expect more in the near future.

5. Fiber Optics Materials

Conventional optical fibers consist of an inner core and a surrounding outer cladding of a lower refractive index material. The attenuation of light in a fiber is a complex phenomena but for practical purposes the internal losses are due to inherent properties of the dielectric core and not on imperfect internal reflections. A patent disclosure for a new type of optical fiber has been submitted by Corning Glass Works which is expected to largely circumvent this problem. This proposal is to use a hollow tube with a highly reflective inside wall. Losses are now governed only by the reflective properties of the coating, no longer by the loss tangent of the core and they are therefore expected to be less than for an equivalent solid core fiber.

This new type of optical fiber is being fabricated by Corning in their Television Products, Market Development Department at Corning, New York. Such hollow tubes have been made down to 10 microns in inside diameter with good control of open area to wall area. In the 10 - 20 micron diameter region this can be as much as 70/30. At smaller diameters, wall thickness remains constant but the hole gets smaller and smaller until it becomes a solid fiber.

This may be the most difficult material, at least initially, to obtain samples of as they must be made specially to order and can be of any desired shape both inside and outside. However, it is possible to obtain samples up to 2" x 2" consisting of a matrix of 10 - 20 micron diameter hollow fibers.

Techniques on how to assemble these individual fiber tubes into a matrix is presently under study. It is hoped these fibers can be bonded together in some way to produce an experimental rear projection screen.

Another group in Corning's Television Products, Market Development Department is making progress on conventional, cladded, solid core, fiber optics. They have been able to build fiber plates which maintain high resolution over a relatively large angular field. We will obtain samples of these and evaluate them as to their applicability to rear projection screens.

B. Laboratory Investigations

1. Spectrophotometer Measurements

Some very preliminary laboratory investigations have been made. One such investigation consisted of determining the spectral transmission curves for six different translucent materials. These are shown in Figure 1.

Key and pertinent data relating to Figure 1:

1.	100% line	Scale 100%
2.	Porous Vicor (new) 5 mm thick	Scale 100%
3.	Porous Vicor (discolored by organic molecules) 4 mm thick	Scale 100%
4.	Polacoat Rear Projection Screen Material .014" thick	Scale 10%
5.	Glass Ceramic from Corning Glass Code 119GIY - 1 mm thick	Scale 10%
6.	Scotch Magic Tape .004" thick	Scale 100%
7.	Vinyl Plastic, clear, calendered .012" thick	Scale 100%

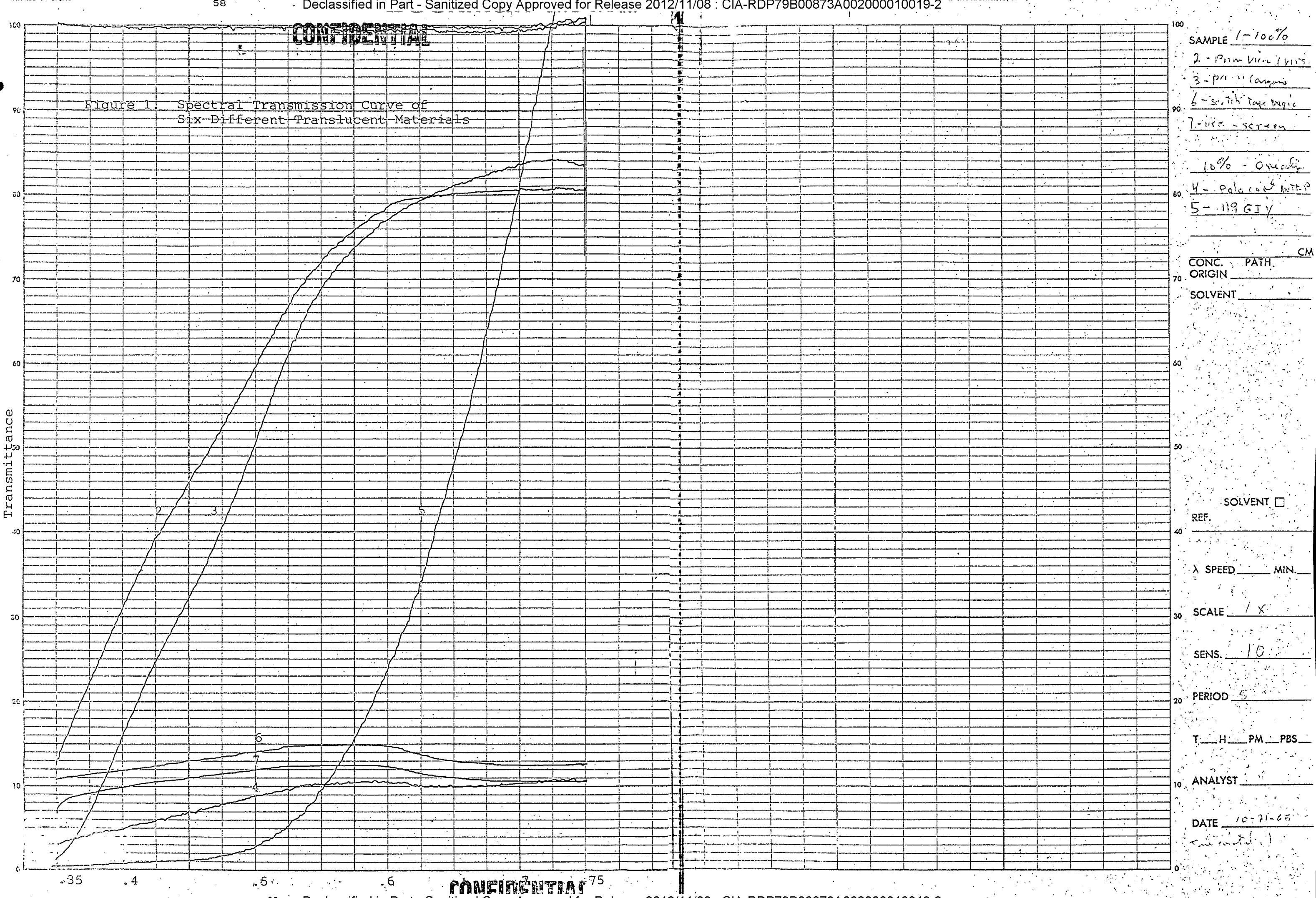


Figure 1: Spectral Transmission Curve of Six Different Translucent Materials

The "Scale 10%" means the 100 mark on the scale along the left edge of Figure 1 corresponds to 10% transmission. It is interesting to note the very low efficiency of the rear projection screen material manufactured by Polacoat Corporation.

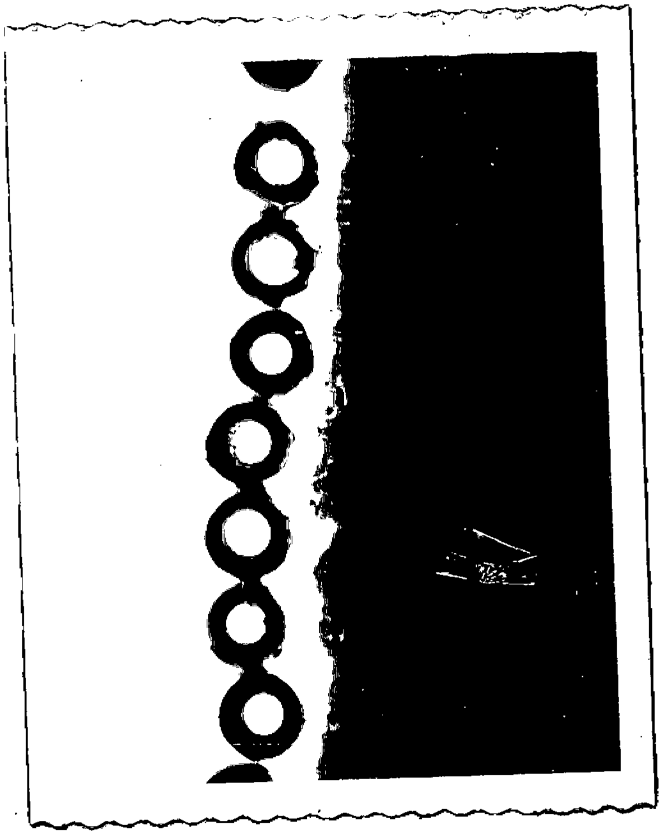
2. Samples of Optical Fibers

Three different types of materials for hollow fiber applications have been obtained. Photomicrographs of them are shown in Figure 2. The fibers in Figure 2a were made from an absorbing Molybdenum impregnated Vicor brand glass and measure 119 microns in outside diameter with about a 56 micron bore. Figure 2b shows fibers made of a non-absorbing glass which range in bore size from 115 to 160 microns and have an almost constant 18 micron wall thickness.

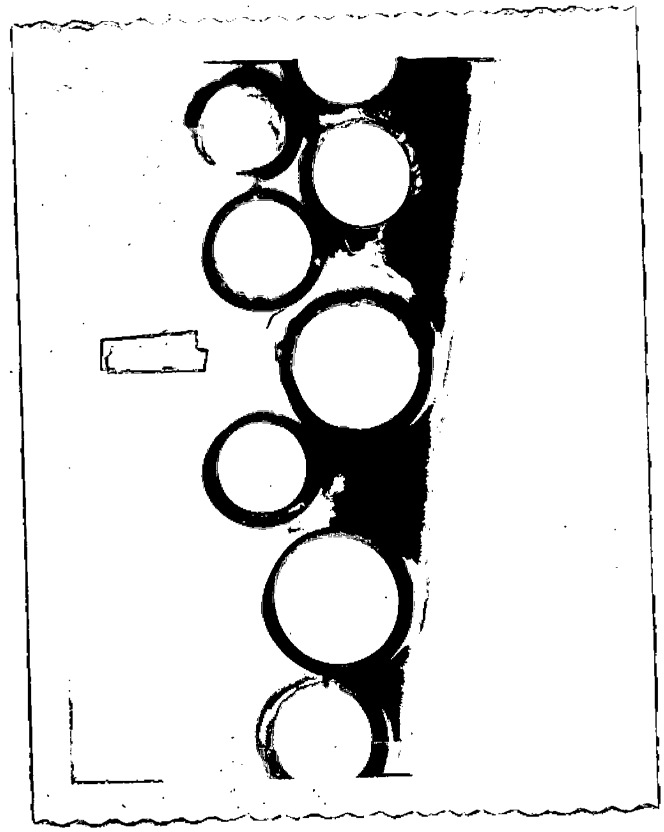
The fibers in Figure 2c measure 81 microns square on the inside with a wall 53 micron thick.

3. Metallizing of Hollow Fibers

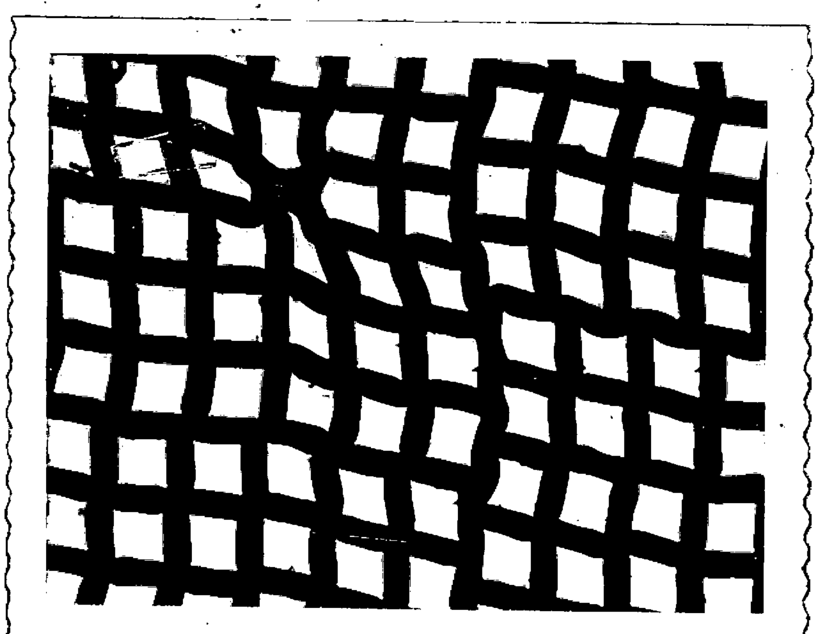
At present the Advanced Products Department of the Technical Products Division at our Corning, New York, facility is attempting to coat the inside of hollow fibers using a new type of coating material. This is a mixture of solvents, organic compounds, and metallic salts. This work is expected to give us an early estimate of the feasibility of plating both fibers and matrices and also an estimate of the requirements, in terms of time and facilities to do this type of work if it proves successful. The results of this effort are expected in the near future.



2a



2b



2c

Figure 2. Photomicrographs of Three Different Hollow Fiber Materials

V. Conclusion

The literature search has shown the state of the art of rear projection screens and projection systems. It has shown the areas of greatest and least accomplishment and where analytical results are needed. It has contrasted the many ideas disclosed in patents with what is practically being done.

The preliminary theoretical investigations reassure us of the validity of present resolution theory as applied to light scattering display materials. It has also provided a good background on resolution measurement which will be important in specifying requirements for laboratory instrumentation to measure the resolution properties of CGW screen materials.

Our preliminary materials investigations have directed us to a wide range of different CGW screen materials. These have in part been examined in our laboratory and will be investigated more thoroughly in later phases of the program. In essence there is every reason to believe new and better screen materials will be developed through this effort.

VI. Proposed Program for Phase II
(Theoretical Investigations)

A. Introduction

In addition to the planned literature and patent search which was required during the first phase of three months, some preliminary measurements on CGW materials showed their definite applicability for rear view screens if certain modifications are made. These results, together with the theoretical information acquired during the first phase, enable us now to concentrate our theoretical investigations only on these parameters which are important to evaluate the various types of material. The second phase of this program will also include the preparation of some instrumentation set ups and preliminary experimental work on selected materials. A more detailed outline is given in the following paragraphs.

B. Theoretical

1. Scattering

Because of the importance of the scattering distribution and its dependence upon particle size, scattering theory will be employed to specify the size of scattering centers in preliminary rear projection screen materials.

2. Resolution

This will be an analytical study of physical factors, such as particle size, screen thickness, scattering characteristics, etc., which degrade resolution.

3. Analysis of Projection Systems

To better understand the influence of system requirements on performance, we will investigate the sensitivity of different projection systems to changes in system parameters, such as ambient light, screen gain, bend angles, projection distances, etc.

C. Instrumentation

Instrumentation will be designed and constructed to measure the following parameters:

1. The angular scattering distribution.
2. The modulation transfer function which is a measure of the resolution of the screen.
3. The color characteristics of the screen.

D. Materials Investigations

We will continue investigating CGW materials and working with our materials groups towards specifying requirements for preliminary samples of rear projection screen materials which have been discussed in Technical Report Section IV, concluding Phase I of the program.